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APPLICATION GUIDE FOR SOURCE PM_{10} MEASUREMENT WITH CONSTANT SAMPLING RATE

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This manual presents a method, Constant Sampling Rate (CSR), which allows determination of stationary source PM-10 emissions with hardware similar to that used for Methods 5 or 17. The operating principle of the method is to extract a multipoint sample so that errors due to spatial variation of particle size and anisokinetic sampling are kept within predetermined limits. Current specifications were designed to limit error due to spatial variations to 10%. The maximum allowable error due to anisokinetic sampling is ± 20%; in essentially all sampling situations, cancellation of sampling error will limit overall anisokinetic sampling error to much less than this value.

This manual specifically addresses the use of the CSR methodology for determination of stationary source PM-10 emissions. Material presented in this manual includes calibration of sampling train components, pretest setup calculations, sample recovery, test data reduction, and routine equipment maintenance.

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FOREWORD

Measurement and monitoring research efforts are designed to anticipate environmental problems, to support regulatory actions by developing an in-depth understanding of the nature and processes that impact health and the ecology, to provide innovative means of monitoring compliance with regulations, and to evaluate the effectiveness of health and environmental protection efforts through the monitoring of long-term trends. The Atmospheric Research and Exposure Assessment Laboratory, Research Triangle Park, North Carolina, has responsibility for: assessment of environmental monitoring technology and systems for air, implementation of agency-wide quality assurance programs for air pollution measurement systems, and supplying technical support to other groups in the Agency including the Office of Air and Radiation, the Office of Toxic Substances, and the Office of Solid Waste.

The environmental effects of PM_{10} particulate matter are of concern to the Agency. Acceptable measurement methodology is critical for proper assessment of the impact on the environment of these emissions from stationary sources. Preparation of a manual which specifies measurement procedures is a key component for assuring reliable test data. This manual was prepared to describe the maintenance and operating procedures for the Constant Sampling Rate approach for measurement of PM_{10} emissions from stationary sources.

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ABSTRACT

This manual presents a method, Constant Sampling Rate (CSR), which allows determination of stationary source PM_{10} emissions with hardware similar to that used for Methods 5 or 17. The operating principle of the method is to extract a multipoint sample so that errors due to spatial variation of particle size and anisokinetic sampling are kept within predetermined limits. If the range of duct velocities would cause the limit on anisokinetic sampling error to be exceeded by a full traverse, the traverse is broken into two or more subtraverses with different sampling nozzles. The number of traverse points is selected to reduce errors due to spatial variation of emissions to acceptable levels while allowing sufficient time for necessary operator decisions between sampling points. In order to provide proper averaging of emissions, the dwell time at each traverse point is proportional to the local duct velocity. Current specifications were designed to limit error due to spatial variations to 10%. The maximum allowable error due to anisokinetic sampling is ±20% for 10 μm particles; in essentially all sampling situations, cancellation of sampling error, and much smaller contributions for particles smaller than 10 μm will limit overall anisokinetic sampling error to much less than this value.

The sampling device described in this manual is Cyclone I of the SRI/EPA five-stage series cyclone. This device provides a 10-μm size cut at a flow rate of approximately 0.5 dscfm; the precise flow rate depends on local stack conditions.

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SYMBOLS

A	Aspiration coefficient (measured concentration/actual concentration)
A_j	Total cross-sectional area of the jet(s) of the PM_{10} stage
A_n	Cross-sectional area of sampling nozzle, ft^2
B	$(2 + 0.617/R)K$
B_{ws}	Water fraction of stack gas
C	Cunningham slip factor
C_m	Concentration of particulate, mg/dNm^3
C'_m	Concentration of particulate matter, gr/dscf
C_p	Pitot tube coefficient for the CSR probe
C'_p	Pitot tube coefficient for Method 2 probe
d	Nozzle diameter
d_j	Diameter or width of one jet of the PM_{10} stage
d_n	Diameter of nozzle n, in.
D	Particle aerodynamic diameter, μm
D_{50}	Cyclone cut diameter, μm
$\bar{D}$	Velocity-weighted average of generic data term, D
D_j	Average value of generic data term, D, for each nozzle size
$D_{p_{stack}}$	Stack differential pressure, in. H_2O
E_n	Collection efficiency for PM_{10} stage n
E_s	Average E_{sam}
E_{sam}	Sampler-only collection efficiency
E_t	Average E_{tot}
E_{tot}	Total (nozzle and sampler) collection efficiency
f_{10}	PM_{10} fraction
f_c	Fraction CO_2
f_o	Fraction O_2
I	Percent isokinetic sampling
K	Particle Stokes number with respect to the nozzle, $\tau v/d$
K_p	85.48 ft/s (lb/mole-°R)
M_d	Dry molecular weight of stack gas, lb/mole
M_{et}	Mass of dye collected in the sampler exit tube
M_{fil}	Mass of dye collected in the backup filter
M_{H_2O}	Molecular weight of water, 18 lb/mole
M_n	Mass of dye collected on PM_{10} stage n
M'_n	Mass of dye collected on all surfaces downstream of PM_{10} stage n
M_{noz}	Mass of dye collected in the sampling nozzle
M_p	Mass of collected particulate (either per stage or total), mg
M_{sam}	Mass of dye collected in the sampler body
M_w	Wet molecular weight of stack gas, lb/mole
n	Number of component changes
P_a	Ambient pressure, in. Hg

P_s	Absolute stack pressure, in. Hg
P_{ST}	Absolute pressure at standard conditions, 29.92 in. Hg
Q_s	Flow rate through the sampler (sampler conditions), acfm
$Q_{s_{ST}}$	Sample flow rate (standard conditions), ft^3/min
R	Ratio of stream velocity to nozzle velocity
Re	Reynolds number
R_u	Ideal gas constant, 21.83 in. Hg-ft^3/mole-°R
S	Standard deviation
Stk	Stokes number, $\tau v/d$, dimensionless
Stk_{50}	Stokes number giving 50% collection efficiency
t_1	Dwell time at the first traverse point, min
t_j	Run time for each nozzle size
T_M	Absolute gas meter temperature, °R
T_s	Absolute stack gas temperature, °R
T_{ST}	Absolute temperature at standard conditions, 528 °R
u	Nozzle velocity, ft/s
v	Stream velocity, ft/s
$V_{\ell c}$	Total volume of liquid collected in impingers or condenser/silica gel, mL
v_{min}	Minimum allowable stack velocity to be sampled with a given nozzle diameter, ft/s
v_{max}	Maximum allowable stack velocity to be sampled with a given nozzle diameter, ft/s
V_M	Volume of gas sample flow through the dry gas meter (meter conditions), ft^3
V_{MS}	Volume of gas sample flow through the dry gas meter (standard conditions), ft^3
v_s	Stack gas velocity, ft/s
V_{WS}	Volume of water vapor in the gas sample (standard conditions), ft^3

γ	Gas meter calibration constant
ΔH	Orifice pressure drop, in. H_2O
$\Delta H_@$	Orifice pressure differential for a flow rate of 0.75 cfm at standard conditions, in. H_2O
ΔP	Velocity pressure head, in. H_2O
ΔP_1	The velocity ΔP at the first traverse point, in. H_2O
$(\sqrt{\Delta P})_{avg}$	Average square root of velocity ΔPs, used to calculate average stack velocity
ΔP_{max}	Maximum allowable velocity pressure to be sampled with a given nozzle diameter, in. H_2O
ΔP_{min}	Minimum allowable velocity pressure to be sampled with a given nozzle diameter, in. H_2O
ΔP_n	The velocity ΔP at traverse point n, in. H_2O
ΔP_{ST}	Velocity pressure drop of standard pitot tube, in. H_2O
θ	Total run time, min
μ	Gas viscosity, micropoise
ρ_{H_2O}	Density of water, 1 g/mL
σ_g	Geometric standard deviation of lognormal distribution
τ	Particle relaxation time $CD^2/18\mu$
Φ	Outside taper or cone half-angle for a sampling nozzle
ϕ	Inside taper or cone half-angle for a sampling nozzle
ψ	0.5 Stk
Ψ_{50}	0.5 Stk_{50}

SECTION 1

INTRODUCTION

To ensure a representative sample of particulate matter is obtained from a flowing gas stream, three key factors must be considered. First, the length of the sampling period must be adequate to formulate an appropriate temporal average of stream conditions. Second, the location and number of sampling points must be chosen so that a spatial average of emissions across the sampling plane is obtained. Finally, sampling must be performed isokinetically so that the sample is not biased with respect to particle size. These conditions are addressed in the EPA methods for measuring total particulate emissions (Methods 5 and 17) by specifying sampling periods which take into account process cycles, traversing techniques rather than single point sampling, and adjustments in sample flow rate (i.e., nozzle velocity) to match local stream velocity at each point of the traverse so that isokinetic sampling is maintained.

However, a size-specific method, such as one for measuring particulate matter of aerodynamic diameter ≤ 10 μm (PM_{10}), must combine the considerations of obtaining a representative sample with the need to segregate the sample into two or more size fractions. Inertial sizing devices such as cascade impactors and sampling cyclones must be operated at a constant flow rate to maintain constant size cuts. For a fixed nozzle size, this precludes any adjustment in nozzle velocity to maintain isokinetic sampling. Without the use of new sampling hardware such as exhaust gas recycle (EGR), a PM_{10} sampling method must then become a compromise between the conflicting requirements of inertial particle sizing and representative sampling.

This manual presents a method, Constant Sampling Rate (CSR), which allows determination of PM_{10} emissions from stationary sources with hardware similar to that used for Methods 5 or 17. The operating principle of the method is to extract a multipoint sample so that errors due to spatial variation of particle size and anisokinetic sampling are kept within predetermined limits. Current specifications were designed to limit error due to spatial variations to 10%. The maximum allowable error due to anisokinetic sampling is ±20% for 10 μm particles; in essentially all sampling situations, cancellation of sampling error and much smaller contributions for particles smaller than 10 μm will limit overall anisokinetic sampling error to much less than this value. This method has been identified in some previous EPA documents as the Simulated Method 5 (SIM-5) or Constant Flow Rate (CFR) method.

Fundamental to a method of this type is the device used to perform the particle sizing required for PM_{10} collection. The device used in development of this method was Cyclone I of the SRI/EPA five-stage series cyclone

(Smith et al., 1979). For this reason, in some portions of this manual, such as Section 7, Sample Retrieval, instructions are given specifically for this device. Another single stage cyclone could be used if its performance has been adequately characterized as specified in Section 2.

This does not mean the use of other devices, such as cascade impactors, should be discouraged. In recognition of the fact that cascade impactors may often be used as the PM_{10} device, key sections of this manual address the use of these devices. Specific instructions concerning performance determination and specification for cascade impactors are given in Section 2. In Section 5, instructions for choosing the sample flow rate and nozzle(s) are given. Once these parameters are fixed, sampling procedures are the same as with a single-stage sampler. This manual does not address sample retrieval, stage size cutpoint determination, or interpolation of data for multiple stages to determine PM_{10}. Acceptance criteria for size cutpoints, once they are determined, are given in Section 9. It is beyond the scope of this manual to provide complete operating instructions for impactors. Numerous manuals are available which provide information in this area. Unfortunately, these manuals also reflect a varying degree of completeness. The impactor manual chosen for use in conjunction with this CSR manual should include discussions of how anomalous behavior, such as particle bounce, may be avoided, the effects of jet-to-plate spacing, and the variation of size cut with Reynolds number. A recommended manual is the "Procedures Manual for the Recommended ARB Particle Size Distribution Method (Cascade Impactors)," by McCain et al. (1986).

This manual is organized so that the user is guided step-by-step through initial use of the method in a field situation. Section 2 describes the basic principles from which CSR was developed and the specifications for the critical sampling hardware. Section 3 describes the procedures by which various components of a CSR system may be calibrated. Activities which are required or recommended prior to field use of the method are outlined in Section 4. Section 5 describes the calculations required to establish the sampling parameters prior to sampling, and Section 6 outlines the steps to follow during operation of a sampling system. Retrieval of the collected sample is described in Section 7. Sections 8 and 9 describe required postsampling checks and analysis of the field data. Routine maintenance of a CSR system is discussed in Section 10. Auditing procedures and recommended standards are described in Sections 11 and 12.

SECTION 2

OPERATING PRINCIPLES

Many different approaches to resolving the dilemma posed by the conflicting requirements of fixed flow rate and representative sampling may be suggested. One approach used frequently in the past for control device evaluation involved operating the sampler at a sufficient number of points in the sampling plane such that the dominant error source would be anisokinetic sampling bias. Because the concentrations of the fine particles, which were the particles of greatest interest, could be measured correctly without sampling isokinetically, this mode of operation was acceptable for the purpose. However, sampling in this manner did not ensure any level of accuracy was to be obtained in the measurement of overall size distributions. Another approach was to operate the sampler at near-isokinetic conditions at a single traverse point. In this case, the errors due to spatial variation in the particle size distribution would be large unless a full traverse of the sampling plane was synthesized from a number of these single-point measurements. This would be very costly in terms of on-site sampling time.

In developing the CSR strategy, a compromise between the options described above was sought. Several specific objectives shaped the details of the method. First, the technique was designed to minimize changes in equipment from that used for Methods 5 or 17. Second, the details of the traversing strategy were selected to limit errors from spatial variation and anisokinetic sampling to the level of more intrinsic errors (such as fluctuations in source emissions or basic measurement inaccuracy). Finally, measurements would be made to provide an average representative of emission rates rather than concentration.

2.1 ERROR DUE TO ANISOKINETIC SAMPLING

To obtain a sample which is unbiased with respect to particle size, one must sample isokinetically. That is, the gas velocity of the sample stream entering the sampling nozzle must match the local gas velocity in the duct from which the sample is being withdrawn. If the gas velocity in the nozzle is greater than the local duct velocity, the flux of large particles through the nozzle cross-section will be less than that for the free stream; large particles are those which do not follow flow streamlines because of their inertia. As a result, the collected mass of large particles will be selectively depleted. Conversely, if the gas velocity in the nozzle is lower than the local duct velocity, the flux of large particles through the nozzle cross-section will be greater than that of the free stream. The collected mass of large particles in this instance will be selectively enriched. The resulting concentration of very small particles in the sample remains unchanged from that in the duct in either case. The resulting concentration of very large particles in the sample approaches the ratio of the duct velocity to the nozzle velocity.

For any given particle diameter, the anisokinetic sampling error may be expressed as the aspiration coefficient, which is defined as the ratio of measured concentration to actual concentration. Belyaev and Levin (1974) developed a semi-empirical relationship for aspiration coefficient, A, in terms of the particle Stokes number, K, and the ratio of stream velocity, v, to nozzle velocity, u.

$$A = 1 + (R - 1)\frac{B}{B + 1} \qquad (2\text{-}1)$$

where R = velocity ratio v/u
B = $(2 + 0.617/R)K$
K = particle Stokes number with respect to the nozzle, $\tau v/d_n$
τ = particle relaxation time $CD^2/18\mu$, seconds
C = Cunningham slip factor
D = particle aerodynamic diameter
μ = gas viscosity, poise
d_n = nozzle diameter

Equation 2-1 shows that, for given stack conditions and particle size, limiting the anisokinetic sampling error becomes a question of limiting the velocity ratio, R. In other words, for a given limit on error due to anisokinetic sampling, maximum and minimum values of R (R_{max} and R_{min}) will yield results within the stated limits. It may also be noted from equation 2-1 that B is proportional to particle diameter squared. This indicates that anisokinetic sampling error decreases with decreasing particle size. In other words, when sampling for PM_{10} emissions, the velocity ratio, R, could be outside the 0.9 to 1.1 range specified for total emissions in Methods 5 and 17 and still retain equivalent accuracy.

The choice of the limits on anisokinetic sampling error for CSR is important. An overly generous range could produce data with an excessive amount of error. At the other extreme, small limits would restrict the velocity ratio to the point that most sites would require multiple nozzle sizes for a complete traverse, which would increase the on-site sampling effort.

2.1.1 Measurement of PM_{10} Emission Rate

For the purposes of PM_{10}, limits of ±20% on error due to anisokinetic sampling were chosen to specify the limits on the velocity ratios, R_{min} and R_{max}. Solving equation 2-1 for R as a function of stream velocity, v, viscosity, μ, sample flow rate, Q, and particles with aerodynamic diameter of 10 μm, the series of curves shown in Figure 2-1 are defined. The upper curves give R_{max} and correspond to the upper limit on A (1.2). The lower curves give R_{min} and correspond to the lower limit on A (0.8). As can be seen from the figure, the limits on R are broad at the smaller stream velocities and approach limits of ±20% at high stream velocities.

Actual sampling error for most sources will be less than the ±20% limit for two reasons. First, point-by-point R values will usually be something less than the limits, R_{min} and R_{max}, and cancellation of errors will occur

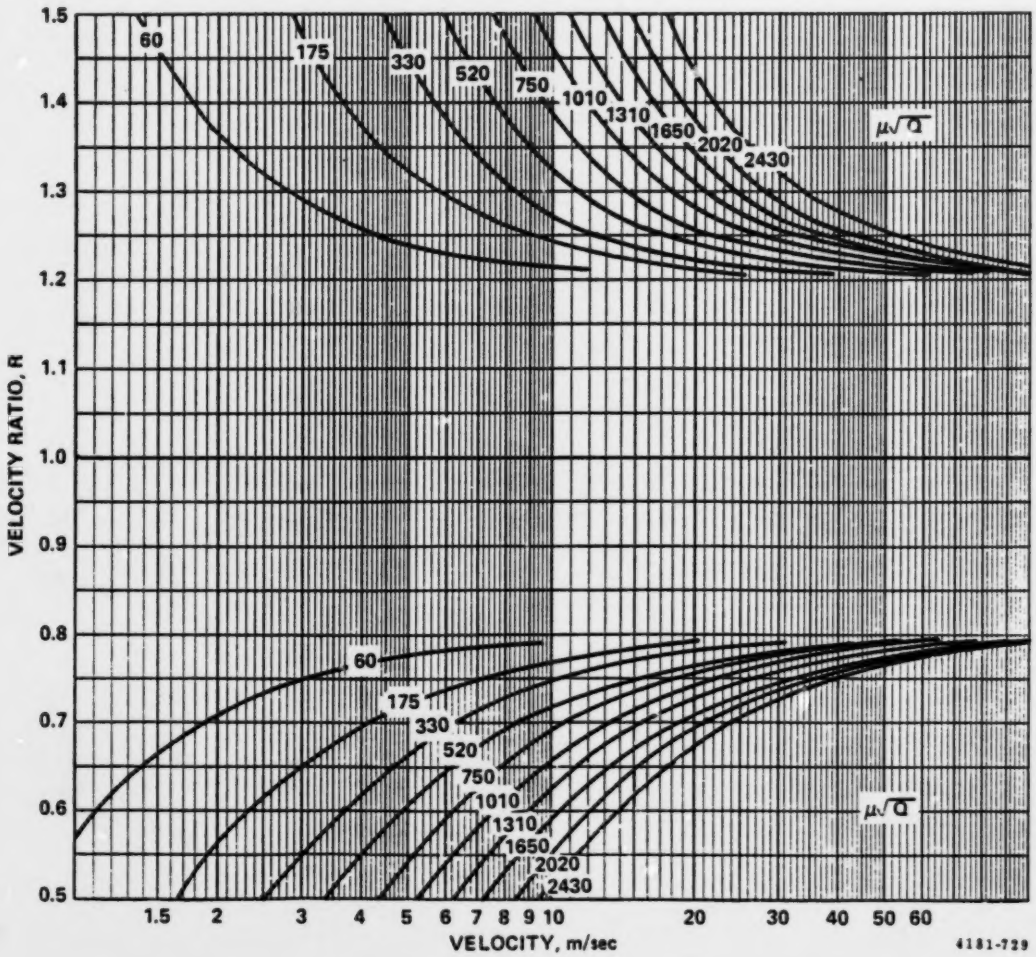


Figure 2-1. Velocity ratio R, duct velocity/nozzle velocity, versus duct velocity giving aspiration coefficient of 1.2 (upper curves) and 0.8 (lower curves) for particles with aerodynamic diameter of 10 μm and gas viscosities ranging from 160 to 280 x 10^{-6} poise. Sampling error of 10 μm particles is less than ± 20% for R-values between an upper and a lower curve.

because R-1 values will be negative at some points and positive at others. Second, the curves shown in Figure 2-1 were determined by assuming a monodisperse sample of 10-μm particles. In actuality, the PM_{10} sample is composed of particles with aerodynamic diameters less than 10 μm.

2.1.2 Measurement of PM_{10} Fraction

Limits on the velocity ratio, R, for measurement of the PM_{10} fraction of total emissions are determined in a slightly different manner than those for the PM_{10} emission rate. This is necessary because of two important differences between the two parameters. First, because anisokinetic sampling introduces both positive and negative errors to the two size classifications of interest (particles less than 10 μm in diameter and particles greater than 10 μm in diameter), there is partial cancellation of the error when the ratio is taken to calculate the PM_{10} fraction. Second, because there is no upper limit on particle size for the portion greater than 10 μm, the ratio B/(B+1) in equation 2-1 must be assumed to be unity for this size fraction when determining the limits on sampling error.

For a particular source, the limit on percent error in measurement of PM_{10} fraction (f_{10}) is approximately the quantity

$$(R - 1)(1 - f_{10}) \times 100$$

where R is the minimum or maximum value of velocity ratio experienced during the sampling run. Limits for acceptable values of R are determined by setting the error to ±10%. The limits then become

$$R_{min} = 1 - \frac{0.1}{1 - f_{10}} \text{ and } R_{max} = 1 + \frac{0.1}{1 - f_{10}} \qquad (2\text{-}2)$$

Determination of these limits requires an estimate of the PM_{10} fraction, so it may be necessary to repeat some runs because of poor estimates of the limits as a result of incorrect values for f_{10} in conjunction with substantial variation of velocity across the sample plane.

2.2 ERROR DUE TO SPATIAL VARIATION

The goal of a traversing strategy should be to reduce error due to spatial variation so that it is not the dominant source of error but is comparable to or less than other sources of error. Extensive analyses have been made of the uncertainty in measurements of total particulate emission caused by spatial variation in process streams. The analysis presented by Shigehara (1982) suggests that 8 to 12 traverse points provide a large reduction in error from one point, whereas additional points provide little additional decrease.

In general, the PM_{10} fraction is expected to be less stratified than total particulate emissions. The lower inertia of the PM_{10} fraction would cause less deviation from gas flow in bends and faster damping from turbulent diffusion once stratification is produced. On the basis of available PM_{10} profiles, Farthing (1983) concluded that Shigehara's data may be used as a

conservative estimate of error due to spatial variation in PM_{10} measurements. Using the 8 to 12 traverse points specified in the CSR protocol is expected to reduce this type of error to less than ±10%.

2.3 SAMPLING HARDWARE

As stated previously, one of the objectives during the development of the CSR technique was to make use of existing sampling equipment. Therefore, the hardware changes required to operate a CSR sampling system have been kept to a minimum. Like a standard total particulate sampling train, a CSR system may be operated with an out-of-stack filter (analogous to Method 5) or an in-stack filter (analogous to Method 17). Block diagrams of the systems are shown in Figures 2-2 and 2-3, respectively. If the CSR train is operated with an in-stack filter, a heated probe is not required, but steps should be taken to prevent condensed moisture from running back into the sampling device and contaminating the sample.

As can be seen from Figures 2-2 and 2-3, the apparent differences between CSR and standard total emissions hardware are confined to the front end of the probe. There are some less obvious differences, however. The sampling flow rate at which a CSR train is operated is set by the requirement that the sample be segregated into two or more specified size fractions. In addition to stack conditions, this flow rate is dependent on the geometry and characteristics of the sampling device. In other words, different sampling devices may have significantly different sampling flow rates. In the case of SRI/EPA Cyclone I, described later in this section, the flow rate which provides a 10-μm cut is approximately 0.50 dscfm. This is considerably lower than the Method 5 or Method 17 nominal flow rate of 0.75 dscfm. To control this flow rate with a reasonable degree of accuracy, a smaller orifice than that typically used for Method 5 (0.180 in.) will be required. Experience has shown 0.130 in. is a practical diameter for the sample orifice when a CSR train is operated with a SRI/EPA Cyclone I. However, this may not be an appropriate size for a different sampling device for the reasons given previously. To minimize uncertainty in choosing the sample orifice size or to prepare for operating the sampling train with a number of sampling devices, a set of orifices should be acquired with the following diameters: 0.180 in., 0.130 in., and 0.093 in.

As Figures 2-2 and 2-3 show, the primary difference between CSR and Methods 5 or 17 hardware is the PM_{10} sampling device. Although a number of particle sizing devices may be considered for use as a PM_{10} device, practical considerations eliminate several of the choices. For the purposes of this method, the only single-stage device which should be considered is an in-stack cyclone. Although a single stage of a cascade impactor may provide the appropriate size segregation, problems such as particle bounce and reentrainment keep this from being an acceptable choice. The multistage device recommended for use with this method is a cascade impactor. Although a series cyclone such as the SRI/EPA five-stage series cyclone provides particle sizing similar to that of a cascade impactor, the mass loading necessary for adequate sample retrieval would require unacceptably long run times for most outlet concentrations.

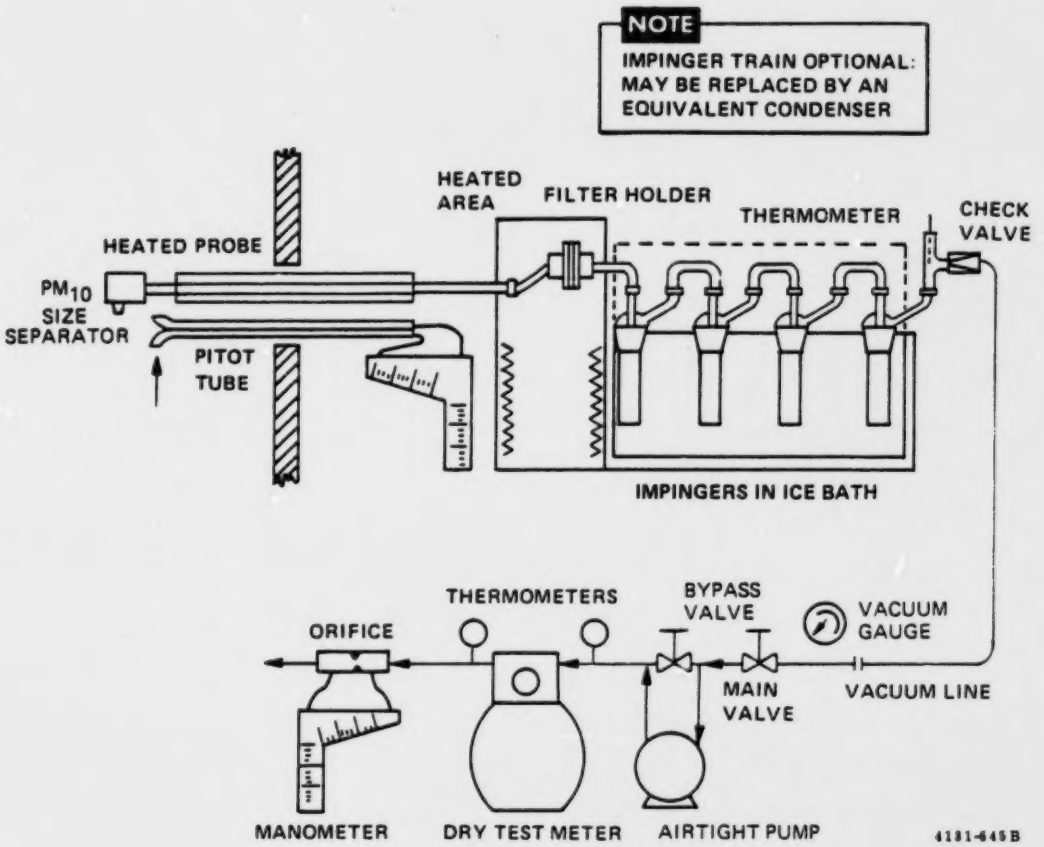


Figure 2-2. PM_{10} particulate sampling train with out-of-stack filter (analogous to Method 5).

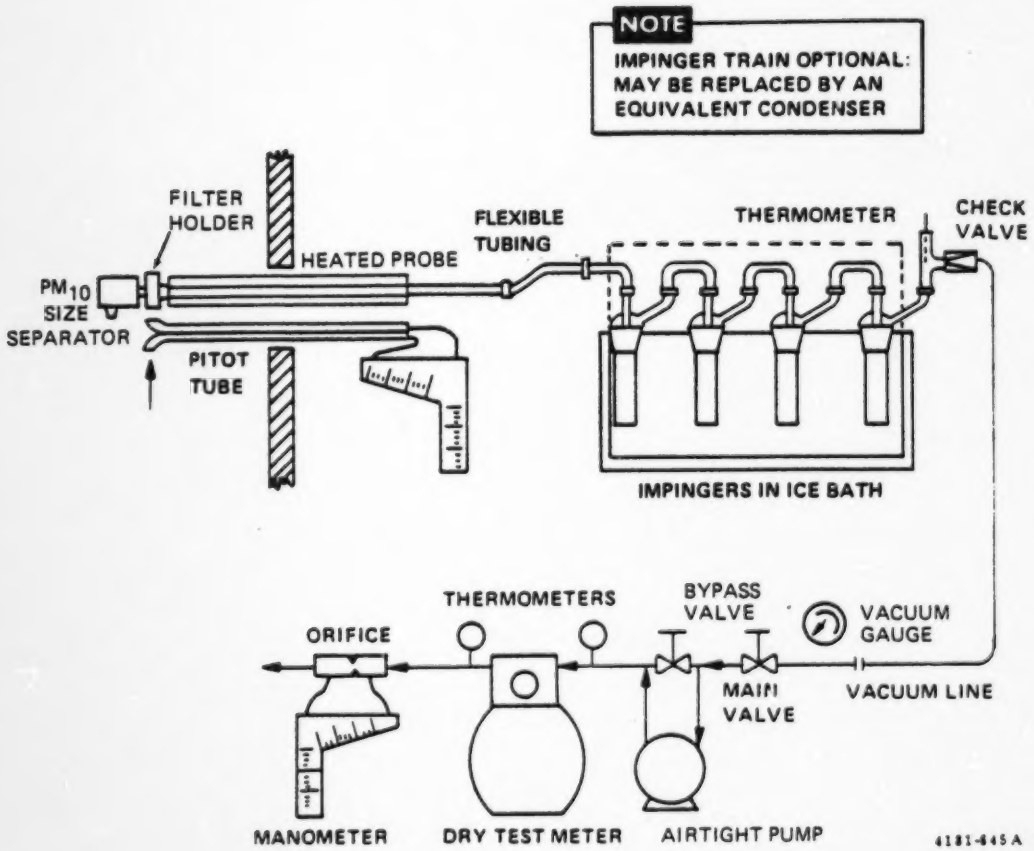


Figure 2-3. PM_{10} particulate sampling train with in-stack filter (analogous to Method 17).

Before any particle sizing device is used as a PM_{10} sampler, it must be shown to meet some specific performance requirements. The procedures by which this may be done are discussed in the following sections for both single-stage and multistage devices (cyclones and cascade impactors, respectively). The specific performance requirements for each of these devices are also given.

2.3.1 Performance Determination for PM_{10} Samplers--Cyclones

To determine that a given cyclone meets the requirements for use as a PM_{10} device, the performance determination procedures outlined in the following text must be performed. The objectives of these procedures are twofold: (1) to calibrate the cyclone (i.e., establish the relationship between collection efficiency, flow rate, gas viscosity, and gas density for the given device) and (2) to determine that cyclone performance satisfies the performance specifications with the sampling nozzles used in practice.

2.3.1.1 Particle Generation--

The particle generating system used for the performance determination of the sampler must be capable of producing solid, monodisperse dye particles with mass median aerodynamic diameters ranging from 5 to 20 µm. The geometric standard deviation (σ_g) for each particle size should not exceed 1.1. Furthermore, the proportion of multiplets and satellites should not exceed 10% by mass.

The size of the solid dye particles delivered to the test section of the wind tunnel should be established by using the operating parameters of the particle generating system. This should be verified during the tests by microscopic examination of samples of the particles collected on a membrane filter. The precision of the particle size verification technique should be 0.5 µm or better, and the particle size determined in this manner should not differ by more than 10% from that established by the system operating parameters.

The monodispersity of the particles should be verified for each test by either microscopic inspection of particles collected on filters or monitoring techniques such as an optical particle counter followed by a multichannel pulse height analyzer. It is preferable that verification of acceptable particle size distribution be performed on an integrated sample obtained during the sampling period of each test. As an alternative, samples obtained before and after each test may be used to verify the size distribution.

To determine cyclone behavior as a function of gas conditions, the system must be operated at a range of temperatures. The dye particles must withstand temperatures from 22 °C (70 °F) to 200 °C (400 °F) without significant change in size, density, or spectral properties in solution (associated with measurement of collected particulate mass). Ammonium fluorescein (available from a number of sources) has been shown to meet these requirements for temperatures up to 350 °F and Pontamine Fast Turquoise 8GLP (available from E.I. DuPont de Nemours and Company) has been shown to meet them up to 400 °F (Smith et al., 1979). However, the thermal integrity of each dye batch should be verified.

The requirements of the apparatus for heating the monodisperse dye aerosol are illustrated in Figure 2-4. A pump with an orifice or other flow meter is used to obtain the test flow rate through the cyclone. The combination of absolute filter/bleed valve allows excess aerosol to escape or additional air to enter as needed. The aerosol stream from the generator passes through a copper tube heated to attain the test temperature. The heat transfer rate and uniformity of heating should be sufficient for the aerosol to attain the test temperature but should not cause the temperature of any interior surfaces to rise above the temperature used for verifying the integrity of the dye. The inlet tube to the cyclone must have the same inside diameter as the inlet diameter of the cyclone. This tube must be cleaned between runs and blanks performed to check for possible effects of reentrainment of particles which accumulate on its interior. The sample port is necessary to collect and examine heated particles for correct size, color, and shape for each measurement run.

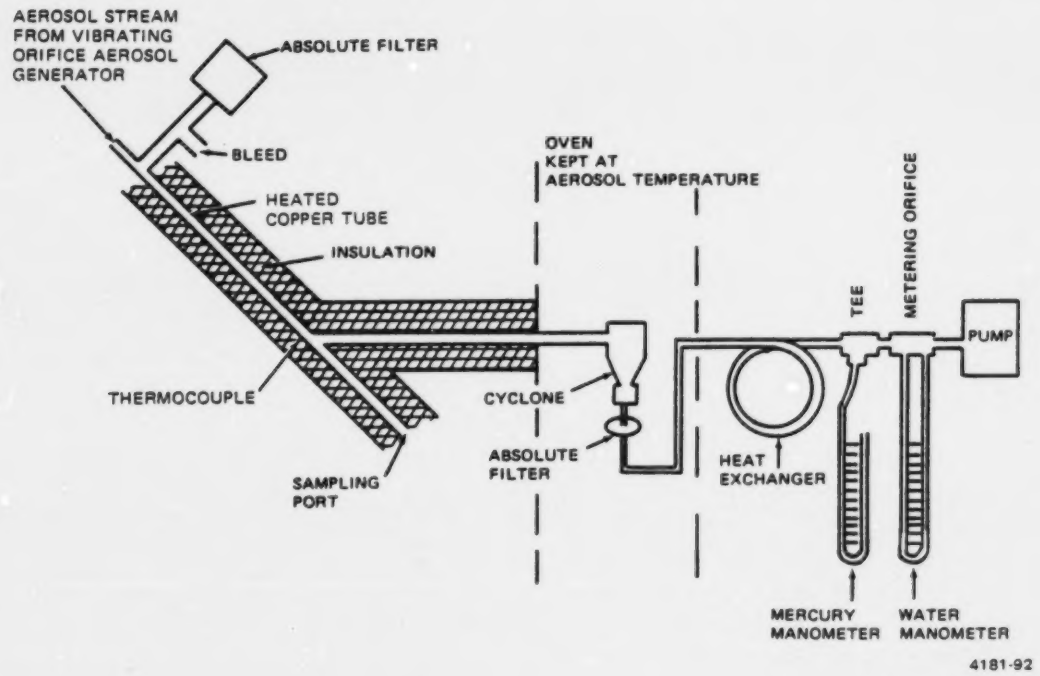


Figure 2-4. Calibration system for heated aerosols.

2.3.1.2 Wind Tunnel--

A portion of the collection efficiency tests must be performed under isokinetic sampling conditions in a wind tunnel or similar apparatus so that the effect of the sampling nozzle on the cyclone performance may be determined. This apparatus must be capable of establishing and maintaining (within 10%) velocities ranging from 7 to 25 m/s.

The velocity of the wind tunnel gas stream in the vicinity of the sampling nozzle should be measured by using an appropriate technique capable of a precision of 5% or better and of a spatial resolution of 1 cm or less (e.g., hot wire anemometry or miniature pitot tubes). The velocity should be constant within 10% over the inlet area of the largest sample nozzle to be used with the PM_{10} sampler. If the sampler obstructs more than 10% of the wind tunnel cross-sectional area, the velocity uniformity must be demonstrated by velocity measurements with the sampler in position and operating.

For each efficiency test, the gas stream velocity should be determined at the beginning of each test and maintained within 10% of the set value by using a suitable monitoring technique with precision better than 5%.

2.3.1.3 Cyclone Calibration --

To achieve the first objective of the performance determination (establish the relationship between collection efficiency, flow rate, and gas conditions) the following procedures should be followed.

The operator should establish operation of the particle generator and verify particle size microscopically. If monodispersity is to be verified by measurements at the beginning and end of the measurement run rather than by an integrated sample, these measurements should be performed at this time. Flow should be initiated through the cyclone at the test value after stable, correct operation of the generator is established. The operator should sample long enough to obtain ±5% precision on total collected mass as determined by precision and sensitivity of the measuring technique. Immediately after completion of sampling, the size of the aerosol particles should be verified microscopically.

The sampled particulate mass is determined by a suitable technique (fluorimetry or absorption spectrophotometry for ammonium fluorescein). The mass collected in the nozzle, PM_{10} sampler body, PM_{10} sampler exit tube, and backup filter (M_{noz}, M_{sam}, M_{et}, M_{fil}, respectively) is determined separately. Each separate surface must be rinsed with an adequate amount of an appropriate solvent to dissolve the collected dye particles, and care must be taken not to contaminate the rinses with dye from other surfaces. Sufficient solvent must be added to each rinse until the rinse volume is suitable for measurement or calculation. The mass of dye in the rinses is to be determined from the spectroscopic measurement by using appropriate blank and standard solutions for reference and quality control.

The total (nozzle and sampler) and sampler-only collection efficiencies (E_{tot} and E_{sam}) may be calculated from the following equations:

$$E_{tot} = 100\% \times (M_{noz} + M_{sam})/(M_{noz} + M_{sam} + M_{et} + M_{fil}) \qquad (2\text{-}3)$$

$$E_{sam} = 100\% \times M_{sam}/(M_{sam} + M_{et} + M_{fil}) \qquad (2\text{-}4)$$

At least two replicates of the above steps should be performed.

The average efficiency should be calculated and recorded as

$$E_t = \frac{\sum_{i=1}^{n} E_{tot}(i)}{n} \qquad E_s = \frac{\sum_{i=1}^{n} E_{sam}(i)}{n} \qquad (2\text{-}5)$$

where $E_{tot}(i)$ and $E_{sam}(i)$ represent individual E_{tot} and E_{sam} values and n equals the number of replicates.

The standard deviation (S) for the replicate measurements should be calculated and recorded as

$$S = \left[\frac{\sum_{i=1}^{n} E^2(i) - \left(\sum_{i=1}^{n} E(i)\right)^2/n}{n - 1} \right]^{0.5} \qquad (2\text{-}6)$$

where E(i) represents $E_{tot}(i)$ and $E_{sam}(i)$.

For n = 2, $S = [E(1) - E(2)]/\sqrt{2}$. If the value of S for E_{tot} exceeds 10% of E_t, the test run must be repeated.

The size cut, D_{50}, of the cyclone is established by either of two sets of measurements. In one set, operating conditions are adjusted to obtain a collection efficiency, E_s, of 50 ±5% for a single particle size. Three replicate runs should be performed with the actual particle size for each run within ±5% of the desired value. In the other set, E_s is measured with at least three particle sizes at the same operating conditions, and linear interpolation in log-probability space is used to determine the D_{50}. In the latter set, the measured E_s values must be between 20 and 80% and include values both below and above 50%.

2.3.1.4 PM_{10} Flow Rate--

To determine the empirical relationship between PM_{10} flow rate and gas conditions, the D_{50} determination described above must be performed for at least three temperatures. The D_{50}'s must be between 5 and 15 μm and measured at temperatures within 60 °C (108 °F) of the temperature at which the cyclone will be used. In addition, one of the measured D_{50}'s must be 10 ± 0.5 μm.

Linear regression analysis is used to determine the relationship between the dimensionless parameters Ψ_{50} ($\equiv 0.5\ Stk_{50}$) and Re, where Stk_{50} is the Stokes number giving 50% collection and Re is the Reynolds number of the gas entering the cylcone.

$$\Psi_{50} = 0.5\ Stk_{50} = D_{50}^2\ \frac{4Q}{18\pi\mu d^3} \qquad (2\text{-}7)$$

and

$$Re = \frac{4\rho Q}{\pi\mu d} \qquad (2\text{-}8)$$

where Q = gas flow rate through the cyclone at the inlet conditions
μ = gas viscosity
d = diameter of the cyclone inlet
ρ = gas density at the cyclone inlet

With the substitution of D_{50} = 10 μm into the resulting relationship, the flow rate for PM_{10} measurements is predicted as a function of gas conditions.

2.3.1.5 Determination of Cyclone/Nozzle Collection Efficiency--
Because the cyclone and sampling nozzles are used as a unit in actual sampling situations, it is necessary to establish that the nozzles do not perturb the particle sizing characteristics of the cyclone as determined by the calibration procedures discussed previously. To do this, collection efficiency tests should be performed for the cyclone/nozzle unit by using the particle diameters and gas velocities shown in Table 2-1. For the appropriate PM_{10} sampler flow rate, the operator should determine the nozzle size appropriate for isokinetic sampling in each of the three velocity ranges shown in the table. If more than one nozzle is suitable for a range, the larger nozzle may be chosen.

After the three nozzle sizes have been determined, the first airstream velocity to be tested in the wind tunnel should be established and verified as described previously. The particle generating system should then be started and the particle size distribution verified. The particle size, as determined by the system operating conditions, must be within the tolerances specified in the table. The operator should begin sampling by establishing the flow rate required for a 10-μm D_{50} in the cyclone.

At the completion of the runs, the total and sampler-only collection efficiencies (E_{tot} and E_{sam}) should be determined from equations 2-3 and 2-4. For each of the three gas stream velocities tested, the average E_t and E_s should be plotted as functions of particle size (D) on semilog paper. Smooth curves should be drawn through all sizes used. The D_{50} for E_s should be defined as the diameter at which the E_s curve crosses 50% efficiency.

TABLE 2-1. PARTICLE SIZES AND NOMINAL GAS VELOCITIES FOR EFFICIENCY PERFORMANCE TESTS OF CYCLONES

Particle Size (μm)[a]	Target Gas Velocity (m/s)		
	7 ± 1.0	15 ± 1.5	25 ± 2.5
5 ± 0.5			
7 ± 0.5			
10 ± 0.5			
14 ± 1.0			
20 ± 1.0			

[a]Mass median aerodynamic diameter.
Number of test points (minimum of two replicates for each combination of gas velocity and particle size): 30.

2.3.2 Performance Specifications for PM_{10} Samplers - - Cyclones

The performance specifications for a PM_{10} cyclone are shown in Table 2-2. To be acceptable for use, the D_{50} for the sampler (determined from the E_s curve as described previously) must be 10 ± 1 μm. In addition, all data points used to determine the E_t curves for each of the gas stream velocities tested must fall within the banded region shown in Figure 2-5. The portion of the acceptance envelope corresponding to large particles is bounded by a vertical line at 12 μm, a horizontal line at 90% efficiency, and a lognormal function (oblique line) with geometric standard deviation (σ_g) of 1.7 and 50% efficiency at 12 μm. The boundary at small particle sizes has a vertical line at 8 μm and horizontal lines and lognormal functions which vary between three ranges of gas stream velocity. These horizongal lines are at 10, 20, and 30% efficiency, respectively, with increasing gas velocity. At the lowest range of velocity the lognormal function has σ_g of 1.7 and 50% efficiency at 8 μm. For the two higher velocity ranges, the lognormal functions have 55% efficiency at 8 μm and values of σ_g of 2 and 2.9 respectively, with increasing gas velocity.

TABLE 2-2. PERFORMANCE SPECIFICATIONS FOR SOURCE PM_{10} SAMPLERS--CYCLONES

Parameter	Units	Specification
1. Collection Efficiency	%	Such that collection efficiency falls within envelope specified in Figure 2-5
2. Sampler 50% cut point (D_{50})	μm	10 ± 1 μm aerodynamic diameter

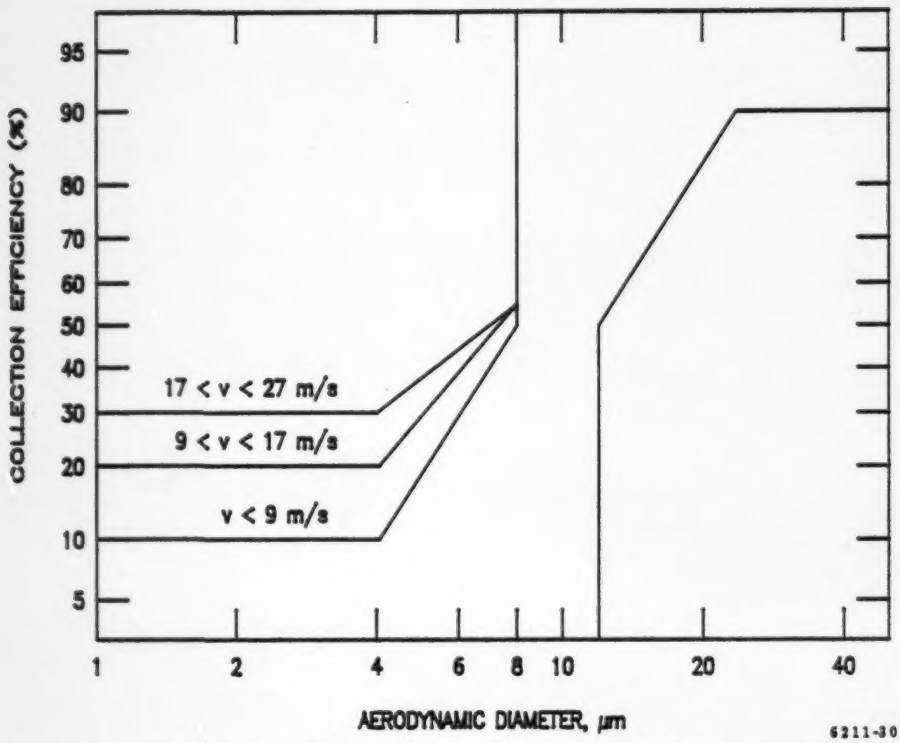


Figure 2-5. Efficiency envelope for PM_{10} sampler (cyclones).

2.3.3 Performance Determination for PM_{10} Samplers--Cascade Impactors

Like those for cyclones, the performance determination procedures for cascade impactors have two objectives: (1) to calibrate the cascade impactor (i.e., determine the Stk_{50} for each of the three PM_{10} stages) and (2) determine the relationship between Stk_{50} and nozzle inlet diameter for the first PM_{10} stage.

The particle generating system and wind tunnel used to perform these tests should be the same as those described previously for cyclones. Therefore, further description of this test equipment will not be given here.

2.3.3.1 Impactor Configuration for Performance Tests--

It is expected, but not necessary, that the complete impactor hardware assembly will be used in each of the sampling runs of these calibration and performance determinations. For these measurements, the first PM_{10} stage

must be calibrated with the nozzles sampling isokinetically in the wind tunnel. The first PM_{10} stage consists of the collection substrate and all upstream surfaces, up to and including the nozzle. This includes all preceding impactor stages which are not designated as PM_{10} stages.

The second and third PM_{10} stages consist of each respective collection substrate and all upstream surfaces up to (but excluding) the collection substrate of the preceding PM_{10} stage. This includes intervening impactor stages, which are not designated as PM_{10} stages. These stages must be calibrated with the collection substrate (impaction surface) of the preceding PM_{10} stage in place so that gas flow patterns existing in field operation will be simulated.

Each of the PM_{10} stages should be calibrated with the type of collection substrate, viscid material (such as grease) or glass fiber used in PM_{10} measurements. It should be noted that most materials used as substrates at elevated temperatures are not viscid at normal laboratory conditions. The substrate material used for calibrations should minimize particle bounce yet be viscous enough to withstand erosion or deformation by the impactor jets and not interfere with the procedure for measuring the collected particulate mass.

2.3.3.2 Impactor Calibration--

Calibration is begun by sampling monodisperse aerosols of sizes within ±67% of the cut size utilized in field PM_{10} measurements. Procedures analogous to those described previously for cyclones are used. However, potential interference of substrate material (grease or glass fiber) entrained in the rinsing process must be eliminated.

The particulate mass collected by PM_{10} stage n, M_n, and particulate mass on all surfaces downstream of stage n, M_n', should be determined. Particulate mass on the upstream side of a jet plate should be included with the substrate downstream of it. However, agglomerates of particles that obviously were removed or reentrained from an upstream surface should be included with the preceding substrate. Collection efficiency for stage n, E_n, is calculated as

$$E_n = 100\% \times M_n/(M_n + M_n') \qquad (2\text{-}9)$$

Equation 2-10 demonstrates the calculation of the dimensionless parameter Ψ ($\equiv 0.5$ Stk, where Stk is the Stokes number) for each measurement.

$$\Psi = 0.5\ \mathrm{Stk} = D^2 \frac{Q}{18\mu A_j d_j} \qquad (2\text{-}10)$$

where D = particle diameter
Q = gas flow rate through the PM_{10} stage at inlet conditions
μ = gas viscosity
A_j = total cross-sectional area of the jet(s) of the PM_{10} stage
d_j = diameter or width of one jet of the PM_{10} stage

E_η should be measured while varying Ψ to empirically determine Ψ_{50}, the value for 50% collection efficiency. Particle bounce can cause efficiency to decrease at high values of Ψ and thus pass through 50% at multiple values of Ψ. Therefore, the calibration data should clearly indicate the value of Ψ_{50} for minimum particle bounce. Impactor efficiency versus Ψ with minimal particle bounce is characterized by a monotonically increasing function with constant or increasing slope as Ψ increases.

2.3.3.3 Determination of Ψ_{50} versus Nozzle Diameter--

The Ψ_{50} of the first PM_{10} stage can potentially decrease with decreasing nozzle size. Therefore, this stage must be calibrated with the nozzle sampling isokinetically in a wind tunnel or similar test apparatus. These nozzles should have diameters ranging from the smallest to the largest likely to be used in PM_{10} measurements. Calibrations should be performed with enough nozzle sizes to provide a measured value within ±25% of any nozzle size used in PM_{10} measurements, thus providing a set of Ψ_{50}-values for the first PM_{10} stage, needed for determining particle size cut in PM_{10} measurements. The Ψ_{50} value for any nozzle size is determined by interpolation between calibration values.

In addition to measuring collection efficiency versus Ψ for determining Ψ_{50}, calibration measurements should be performed for the first stage at values of Ψ low enough that the efficiency of stage one, E_1, is between 20 and 30%. This data point and all other data (efficiency and Ψ) available for any nozzle diameter are relevant to the performance specification in the next section.

2.3.4 Performance Specifications for PM_{10} Samplers--Cascade Impactors

As can be seen from Figure 2-6, the acceptance envelope for a candidate PM_{10} impactor stage is analogous to that for cyclones with the exception that the abscissa has been changed from aerodynamic particle diameter to values of square root of Ψ/Ψ_{50}. To determine if a given impactor stage meets the performance criteria, efficiency versus the square root of Ψ/Ψ_{50} should be plotted. For the first stage, the data plotted should be those obtained with each of the nozzle diameters tested. All data must fall within the banded region of Figure 2-6 if the stage is to be accepted.

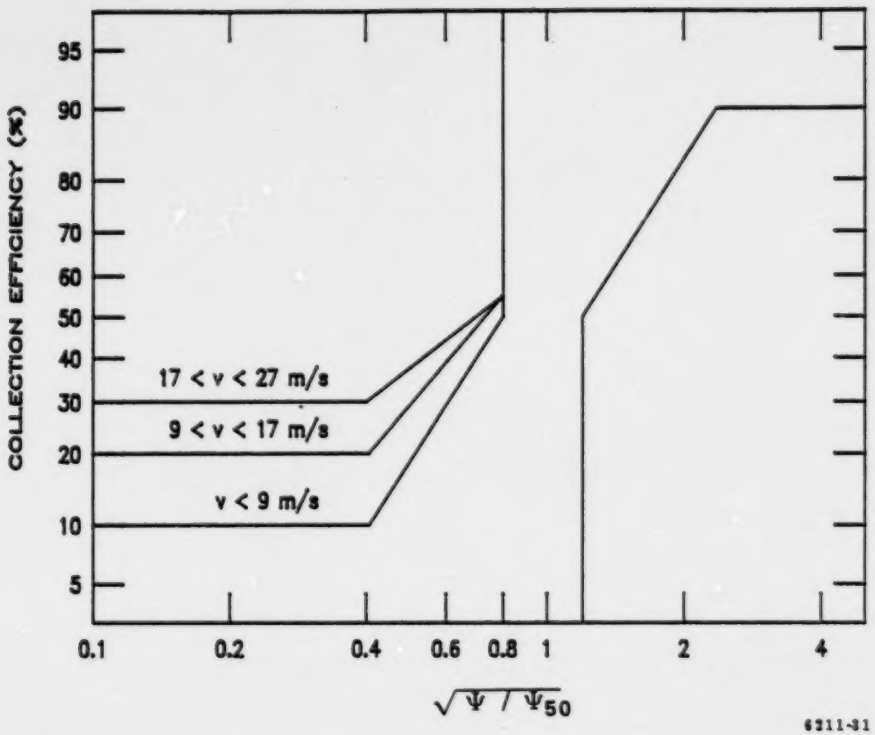


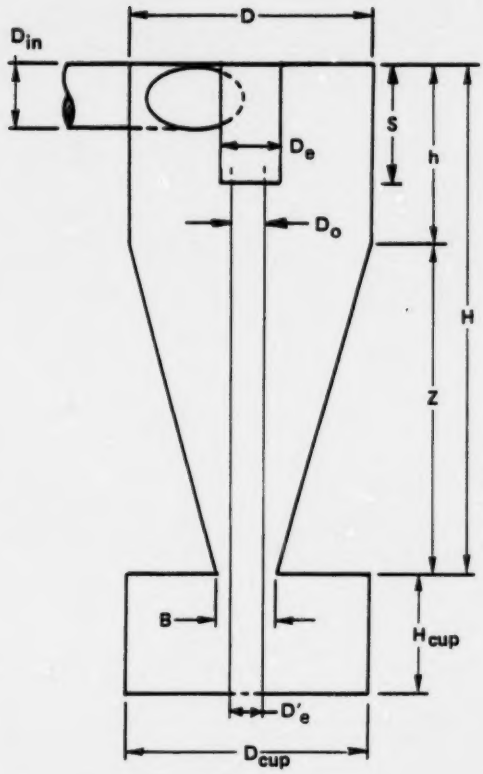
Figure 2-6. Efficiency envelope for PM_{10} sampler (cascade impactor).

2.3.5 SRI/EPA Cyclone I

One sampling device known to meet the performance specifications given previously is the commercially available version of Cyclone I, the first stage of the SRI/EPA five-stage series cyclone. The outer dimensions and physical appearance of the cyclone may vary, depending on the specific commercial source. The critical inner dimensions, however, are standardized to the original design parameters, as can be seen in Figure 2-7. Laboratory calibrations (Farthing and Williamson, 1985) have shown Cyclone I produces a 10-μm D_{50} at a flow rate of approximately 0.5 dscfm; the precise flow rate will depend on local stack conditions.

CYCLONE I DIMENSIONS

BOTTOM EXIT



	DIMENSIONS $\left(\begin{matrix}\text{cm} \pm 0.02 \\ \text{in.} \pm 0.01\end{matrix}\right)$											
	D_{in}	D	D_e	B	H	h	Z	S	H_{cup}	D_{cup}	D'_e	D_o
cm	1.27	4.47	1.50	1.88	6.95	2.24	4.71	1.57	2.25	4.45	1.02	1.24
in.	0.50	1.76	0.59	0.74	2.74	0.88	1.85	0.62	0.89	1.75	0.40	0.49

5595-71 A

Figure 2-7. Cyclone I dimensions.

2.3.6 Sample Nozzles

The anisokinetic error limits for CSR are broad enough that multiple nozzles for a single traverse will seldom be necessary. However, at some sources, the temporal or spatial variation of stream velocity is sufficient to require more than one nozzle. The frequency of tests in which one nozzle size is not sufficient for the complete traverse is related to the increments of nozzle sizes available. Small increments for the nozzle sizes increase the likelihood that a nozzle size will be available to give a nozzle velocity near the mean stream velocity. In this case, $|\bar{R} - 1|$ is at its lowest possible value; moreover, the likelihood is then less that stream velocities will exceed the limits for the chosen nozzle. Thus using smaller nozzle increments simplifies the measurements and improves the accuracy.

The set of nozzle diameters found to provide a sufficient number of increments is shown in Table 2-3. The nozzle velocity corresponding to each diameter for the Cyclone I PM_{10} flow rate at the given stack conditions and the limits on stream velocity for acceptable use of each nozzle are also shown. The minimum and maximum velocity variations which may be encountered when using each nozzle are given in the last two columns of the table. The full range of nozzle diameters shown in the table will not be required in most instances. In other words, sampling situations will seldom be encountered which require the smallest or largest nozzle diameters shown in the table.

TABLE 2-3. CSR NOZZLE DIAMETERS (in.) AND VELOCITY LIMITS (ft/s)[a]

Nozzle Diameter	Nozzle Velocity	Min. Stream vel. (A=0.8)	Min. vel. ratio	Max. Stream vel. (A=1.2)	Max. vel. ratio	Velocity Variation (+/-)	
0.136	100.9	76.4	0.76	124.0	1.23	0.15	0.24
0.150	82.9	61.5	0.74	102.8	1.24	0.15	0.25
0.164	69.4	50.1	0.72	86.8	1.25	0.17	0.26
0.180	57.6	40.0	0.70	73.0	1.27	0.19	0.29
0.197	48.1	31.6	0.66	61.8	1.29	0.21	0.31
0.215	40.4	24.4	0.60	52.9	1.31	0.25	0.35
0.233	34.4	18.1	0.53	46.0	1.34	0.31	0.41
0.264	26.8	13.4	0.50	37.3	1.39	0.35	0.45
0.300	20.7	10.4	0.50	30.5	1.47	0.39	0.49
0.342	16.0	8.0	0.50	23.9	1.50	0.40	0.50
0.390	12.3	6.1	0.50	18.4	1.50	0.40	0.50

[a]For dry gas composition (% volume) and water fraction:

N_2	O_2	CO_2	CO	H_2O
79	4	16	1	0.06

For gas conditions (°R, in. H_2O, and in. Hg):

T	ΔP	P_{bar}
760	-2	29.5

Because of the impact the nozzle geometry may have on performance of the PM_{10} device, specification of nozzle inlet diameters is not sufficient to guarantee acceptability. Numerous laboratory tests with SRI/EPA Cyclone I have resulted in the development of the nozzle design shown in the Figure 2-8. The critical geometric parameters shown in the figure are specified in Table 2-4 for the range of nozzle diameters discussed previously. The inside taper or cone angle, Φ, for each of the nozzle diameters was determined from Figure 2-9. This figure gives the optimum cone angle, as determined from laboratory tests, for any given nozzle inlet diameter. The outside taper, Φ, should be 15° and the inlets sharp-edged so that the criteria of Belyaev and Levin (1972) for negligible particle bounce from the inlet will be met. The length of straight section at the nozzle inlet, ℓ, should not exceed 0.05 in. Longer inlet sections may result in the development of velocity profiles in the nozzle which may seriously perturb performance of the PM_{10} device or contribute to excessive particle losses in the nozzle. The total length, L, for the nozzle diameters (d_n) given in Table 2-4 range from 2.653 to 1.45 in. The minimum length of 1.45 in. was chosen to position the nozzle inlet a sufficient distance away from the body of the PM_{10} sampler so that the flowstream would not be disrupted. For nozzles with larger inlet diameters, a straight section at the nozzle outlet (after the expansion from the inlet diameter to the outlet dimension, 0.50 in.) will be necessary to meet this minimum length requirement.

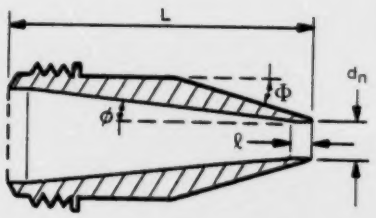


Figure 2-8. PM_{10} nozzle design. L = total length of nozzle; d_n = nozzle inlet diameter; ℓ = straight inlet length; ϕ = inside cone angle; Φ = outside taper angle.

TABLE 2-4. PM_{10} NOZZLE GEOMETRIES

Nozzle Diameter, d_n (inches)	Cone Angle, ϕ (degrees)	Outside Taper, ϕ (degrees)	Straight Inlet Length, ℓ (inches)	Total Length, L (inches)
0.136	4	15	<0.05	2.653±0.05
0.150	4	15	<0.05	2.553±0.05
0.164	5	15	<0.05	1.970±0.05
0.180	6	15	<0.05	1.572±0.05
0.197	6	15	<0.05	1.491±0.05
0.215	6	15	<0.05	1.45 ±0.05
0.233	6	15	<0.05	1.45 ±0.05
0.264	5	15	<0.05	1.45 ±0.05
0.300	4	15	<0.05	1.48 ±0.05
0.342	4	15	<0.05	1.45 ±0.05
0.390	3	15	<0.05	1.45 ±0.05

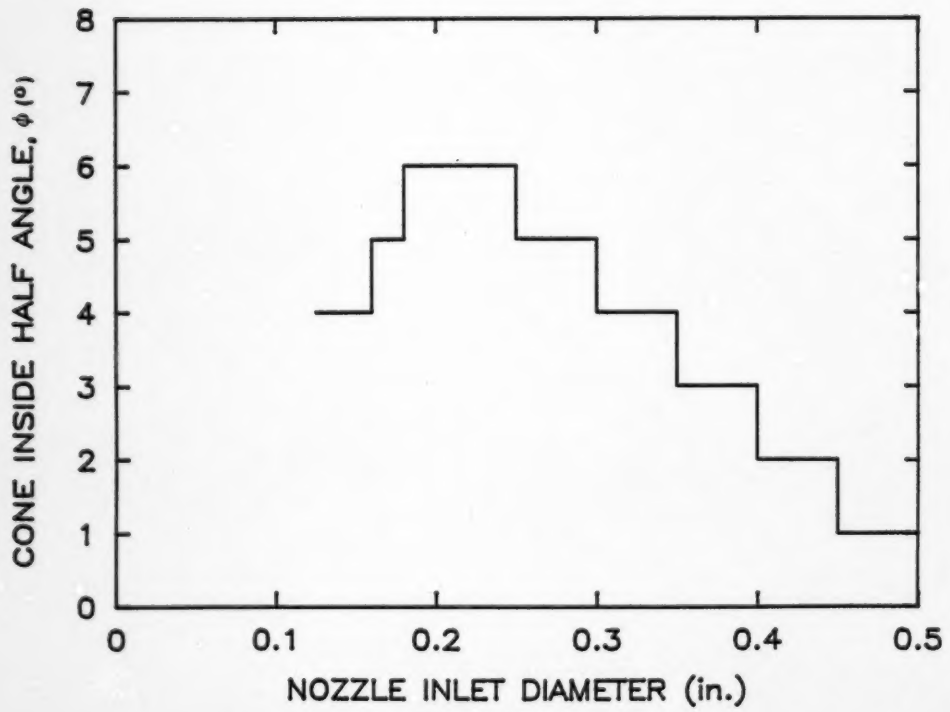


Figure 2-9. Optimum inside cone angle, ϕ, for various nozzle inlet diameters.

SECTION 3

CALIBRATION

As for Method 5 or Method 17, calibration of specific components of a CSR sampling system is required. It is recommended a notebook or other record be kept of all calibration data pertinent to each system. This record should contain the complete calibration history of each device requiring such service (i.e., flow metering devices, pitot tubes, nozzles, thermocouples, and Magnehelic® gauges). A separate record may be desirable for support equipment, such as balances and field barometers, which are not directly connected with the system.

3.1 FLOW METERING SYSTEM

The best calibration of a flow metering device is achieved when the calibration data are restricted to the range of expected use. The defined Method 5 flow rate of 0.75 dscfm provides a finite range of flow rates over which the flow metering system should be calibrated. However, the PM_{10} flow rate is dependent on the characteristics of the sampler used and cannot be easily defined as a single value. This makes defining a calibration range for the flow metering devices difficult at best. For the purposes of this manual, the PM_{10} flow rate at typical meter box conditions is assumed to be 0.50 acfm. It is up to the reader to determine the applicability of this flow rate to his particular system.

The flow metering devices of a CSR system (dry gas meter and sample orifice) should undergo a stringent laboratory calibration before field use. In addition to this initial acceptance testing, the calibration should be checked after each test series. This calibration check procedure ensures that the calibration parameters assigned to the flow metering devices are still valid without requiring the level of effort of the initial calibration. Should the results of the calibration check fall outside acceptable limits, the flow metering device in question should be recalibrated according to the initial calibration procedure.

Before any calibration, a leak check of the metering system should be performed. This should be done for both the vacuum (negative pressure) and positive pressure portions of the train as prescribed in Method 5 (U.S. EPA, 1977).

A calibrated wet test meter or any other such calibration standard should be used to calibrate the flow metering system. The outlet of the calibration standard should be connected to the sample inlet of the control console. Before starting the calibration, the operator should run the system vacuum pump for 15 min. with the orifice meter pressure drop (ΔH) set at approximately 0.5 in. H_2O to allow the pump to warm up and to wet the

interior surface of the wet test meter. The calibration should be performed as required in EPA Reference Method 5 for a range of orifice ΔH settings (0.5, 1.0, 1.5, 2.0, 3.0, and 4.0 in. H_2O). The minimum wet test meter volume for each run should be 5.0 ft^3, except for the two lowest flow rates, for which a volume of 3.0 ft^3 is acceptable. The data should be recorded as requested in Method 5.

A calibration check should be performed on all of the flow metering devices after each field test series. The posttest calibration check should consist of three calibration runs at a single orifice setting. This orifice setting should be representative of the orifice settings used during the field test. The run procedure should be the same as described for the initial calibration.

If the dry gas meter calibration factor, γ, deviates by less than 5% from the initial calibration factor, then the calibration constant assigned to the meter is still valid. If the posttest calibration check yields a calibration factor outside this limit, the gas meter should be recalibrated by using the initial calibration procedure.

The average ΔH recorded during the calibration check should be compared with that obtained from the calibration equation for the device. To calculate the ΔH from the calibration equation, the wet test meter flow rate corrected for temperature and pressure should be used. If the recorded pressure drop varies from the calculated value by more than 10%, the orifice should be recalibrated.

If the dry gas meter requires recalibration, for the purposes of data reduction, use whichever coefficient (initial or recalibrated) yields the lower gas meter volume.

3.2 PITOT TUBE

The construction, configuration, and calibration specifications outlined in EPA Reference Method 2 (U.S. EPA, 1977) should be applied to the CSR pitot tube. The pitot tube should be located at the side of the sampling nozzle furthest from the sampling device axis. To check the pitot tube for leaks, one end of the tube should be plugged and a positive pressure applied at the opposite end. If the tube will not maintain pressure, a soap solution can be used to identify the location of any leaks. If the CSR pitot tube requires calibration, the velocity pressure drop, ΔP, should be measured with a standard pitot tube and the S-type CSR pitot tube at the same point within a cross-section of a straight run of ductwork for a desired range of gas velocities. The CSR pitot tube should be calibrated as used; that is, the complete sampler assembly should be used in pitot tube calibration determinations. The CSR pitot tube should be calibrated twice, as recommended in Method 2, reversing the direction of the legs during the second calibration. For each velocity, a pitot tube coefficient is determined as

$$C_p = 0.99 \left(\frac{\Delta P_{ST}}{\Delta P_{CSR}}\right)^{1/2} \qquad (3\text{-}1)$$

where C_p = S-type pitot tube coefficient, dimensionless
0.99 = C_p value for standard pitot tube, dimensionless
ΔP_{ST} = velocity pressure drop of standard pitot tube, inches of water
ΔP_{CSR} = velocity pressure drop of CSR S-type pitot tube, inches of water

The average value of C_p for each direction over the range of velocities used should be calculated.

3.3 SAMPLING NOZZLES

A micrometer should be used to measure the inside diameter of the nozzle to the nearest 0.001 in. Three separate measurements should be made, each based on a different diameter, and the average of the measurements should be calculated. The largest deviation from the average should not exceed 0.004 in. If the variation is more than 0.004 in., the nozzle should be reshaped and recalibrated.

3.4 THERMOCOUPLES

The thermocouples used to measure the various temperatures within the sampling train should be checked to ensure they are properly calibrated before they are installed in the system. A two-point calibration check using an ice bath and a boiling water bath should be performed as outlined in EPA Reference Method 2. If any individual thermocouple does not produce a reading within ±1.5% of the absolute reference temperature, it should be replaced with another thermocouple of the same type. If all thermocouples show a bias, the readout should be adjusted or recalibrated according to the manufacturer's procedure.

3.5 MAGNEHELIC® GAUGES

The calibration of the Magnehelic® differential pressure gauges should be checked prior to field use and periodically thereafter to prevent invalidation of test data. Before calibration, the Magnehelic® gauge with no applied pressure should be adjusted to read zero using the external zero-adjust screw. To perform a calibration check, ΔP values, as read from the Magnehelic® gauge, should be compared with those from an inclined manometer at a minimum of three points. The ΔP values read from the Magnehelic® gauge should not deviate from the inclined manometer readings by more than 5% at any point.

3.6 SUPPORT EQUIPMENT

The field barometer should be adjusted initially and before each test series to agree with a standard (a mercury-in-glass barometer or the pressure reported by a nearby National Weather Service station) to ± 0.1 in. Hg.

The calibration of all balances to be used during a test series should be checked initially with class-S weights. Triple beam balances should be within ±0.5 g of the standard. Analytical balances should agree to ±2 mg of the standard. Balances which fail to meet these criteria should be adjusted or returned to the manufacturer.

SECTION 4

PRESAMPLING ACTIVITIES

Preparation of the CSR sampling system for field use requires much the same effort as preparation for Method 5 or Method 17 sampling (U.S. EPA, 1977). Some type of pretest calibration or operation check is necessary for most components of the system. This is also true of supporting equipment such as analytical balances. Sampling reagents also require preparation prior to field use. In several cases, the presampling activities described below are similar to or the same as those required for Method 5.

4.1 EQUIPMENT CALIBRATION AND CHECKS

All sampling nozzles should be inspected for damage and repaired where necessary. The nozzles should be cleaned with tap water, deionized water, and finally acetone. The inside diameter of each nozzle should be measured to the nearest 0.001 in. as described in Section 3 of this manual. The knife edge of the nozzle should be protected during shipment by serum caps or similar covers.

The PM_{10} sampler and filter holder should be ultrasonically cleaned with tap water and rinsed with deionized water. After a final rinse with acetone, the sampler assembly should be allowed to air dry. An adequate supply of Viton or silicone rubber O-rings should be available for replacement of worn O-rings in these devices.

The openings of the pitot tube should be visually inspected for damage such as dents or nicks. A check should also be made for proper alignment. The two legs of the pitot should be in a straight line so that the opening of one leg is directed 180° from the other. If damage or misalignment is evident, the pitot tube should be repaired or replaced. If repairs are made, the pitot tube should be recalibration, as described in Section 3.

The lines of the sampling probe, including the pitot lines, should be cleaned before field use. The lines should be cleaned internally by rinsing, first with tap water, then deionized water, and then acetone. The lines should be rinsed a final time with acetone and allowed to air dry. If a heated probe is used, the heating system should be checked for proper operation. (If problems are encountered, see Section 10 of this manual for troubleshooting guidelines.)

The water dropout system (condenser and drying column) should be checked for leaks. The condenser should be cleaned with deionized water and rinsed with acetone. The condenser should be inverted to ensure total drainage and allowed to air dry.

The system flow metering devices (dry gas meter and orifice) should have appropriate calibration factors assigned to them. A pretest calibration check, performed according to the procedure outlined for posttest calibration checks in Section 3, is recommended to ensure the calibrations are still valid. Although pretest calibration checks of the flow metering devices are not required and do not take the place of the posttest checks, they are useful for detecting problems prior to field use. Such a pretest calibration check is strongly recommended if the system has not been used for some time.

It is recommended, but not required, that the calibration of the Magnehelic® pressure differential gauges be checked prior to field sampling. As with the flow metering system, this is strongly suggested if the system has not been used for an extended period of time.

All system temperature sensors (thermocouples, temperature gauges, etc.) should be checked against a mercury-in-glass thermometer at ambient temperature.

Finally, it is recommended that a leak check of the complete system be performed before it is shipped. The system should be assembled from the probe (it is not necessary to include the nozzle or PM_{10} sampler) to the control console. The probe should be capped and the system leak-checked at 15 in. Hg vacuum. Leak rates in excess of 0.02 cfm should be corrected. Each leg of the pitot tube should be leak-checked, including the umbilical lines and the differential pressure gauge.

4.2 PREPARATION OF SAMPLING REAGENTS

Used silica gel should be regenerated by drying at 350 °F for 2 h. New silica gel may be used as received. Several 200- to 300-g portions may be weighed in airtight containers to the nearest 0.5 g. The total weight for each container should be recorded. As an alternative, the silica gel may be weighed in the drying column at the test site.

Quartz fiber is the recommended filter material because it is more resistant to chemical reactions when exposed to stack gases. Filters should be desiccated and weighed as required for EPA Reference Method 5. To prevent the loss of filter cake, it is recommended that aluminum foil envelopes be made to enclose the filter. If used, these envelopes should be desiccated and weighed with the filter.

Aluminum foil envelopes can also be used to collect the PM_{10} cyclone catch. These foil envelopes should be uniquely identified, desiccated, and weighed in the same manner as the filters.

Aluminum weighing dishes or small glass beakers may be used to collect and evaporate the rinses from the sampling device. These containers should be cleaned thoroughly, labeled, desiccated, and weighed prior to use. If the sampling train is operated in a Method 5 configuration, a larger glass beaker or similar container will be needed for probe rinses.

Acetone for sample recovery should be reagent grade with less than 0.001% residue. Acetone blank determinations to ensure residue levels are acceptable may be made before field use or as part of sample recovery.

SECTION 5

SAMPLING PARAMETERS

The sampling parameters which must be dealt with in the CSR procedure are the same as those in EPA Methods 5 or 17 (U.S. EPA, 1977), with the addition of those for particulate mass for each size fraction. However, the two types of procedures are substantially different in terms of control of sampling parameters. In the CSR procedure, sample flow rate is determined by the requirement that the size separation device maintain fixed size cut(s) at or near 10 μm (aerodynamic). For a single-stage cyclone sampler, this flow rate is determined uniquely by the gas composition and temperature of the process stream. For a cascade impactor, the gas composition and temperature determine a range of permitted flow rates from which to choose before sampling is initiated.

Because flow rate cannot be adjusted during a sampling run to match nozzle velocity with the velocity of the gas stream, thus eliminating errors associated with anisokinetic sampling, the nozzle(s) must be carefully selected. First the sample flow rate is determined, then the range of stream velocities at which sampling is to be performed determines the nozzle(s) to be used. For each nozzle diameter, there is a range of stream velocities which correspond to a permissible level of anisokinetic sampling error. Usually, the stream velocity in a sampling plane will be uniform enough that one nozzle size will be acceptable for the entire range of stream velocities. However, for process streams with wide variation of velocity, it may be necessary to use more than one nozzle for a complete traverse of the sample plane.

A third difference between CSR and other methods for particulate emissions involves the sample duration, or dwell time, at each traverse point. In Method 5 or 17, the dwell time is the same for all traverse points. A velocity-weighted average of the measured concentration, or emission rate, is obtained when the sample flow rate is adjusted proportionally to the local stack velocity, as described previously. Because the sample flow rate cannot be adjusted when the CSR method is used, a velocity-weighted concentration is obtained by adjusting the dwell time at each point to be proportional to the local stack velocity.

These differences between the methods manifest themselves in the setup calculations required before a sampling run. This section presents the governing equations and describes the calculations required to determine the CSR sampling parameters. In some cases these calculations are much the same as those required for Methods 5 or 17. References to the appropriate EPA method will be cited in these situations. Only those equations and calculations which are unique to CSR will be discussed in detail here.

5.1 PRELIMINARY MEASUREMENTS

5.1.1 Method 1

Before the appropriate sampling parameters can be calculated, some preliminary determinations must be made. First, the number of traverse points required for CSR should be determined from Figure 5-1. The procedures and requirements for this determination are the same as Method 1. For rectangular stacks, the equivalent duct diameter should be calculated as in Method 1 (U.S. EPA, 1977). The traverse points should be located within the duct as described in Method 1.

5.1.2 Methods 2, 3, and 4

When the number of traverse points and their locations within the duct have been decided upon, the stack temperature and velocity at each of these points should be determined by Method 2 (U.S. EPA, 1977).

The concentration of the primary stack gas constituents (i.e., oxygen, carbon dioxide, nitrogen, carbon monoxide, and water vapor) may be determined from Method 3 (U.S. EPA, 1977) and Method 4 (U.S. EPA, 1977) data. With this information, the gas dry and wet molecular weights may be determined from the following equations:

$$M_d = 32(f_o) + 44(f_c) + 28(1 - f_o - f_c) \qquad (5\text{-}1)$$

$$M_w = M_d(1 - B_{ws}) + 18B_{ws} \qquad (5\text{-}2)$$

It may be necessary to perform additional testing according to standard methods in instances where the stack gas composition is influenced by gases other than those listed above. For example, when gases from a high-sulfur source are sampled, Method 6 (U.S. EPA, 1977) testing should be performed to determine the percentage of SO_2 present in the process gas, and this percent SO_2 should be taken into account when determining the dry molecular weight.

5.2 SAMPLE FLOW RATE AND NOZZLE SELECTION FOR A SINGLE-STAGE CYCLONE SAMPLER

5.2.1 Sample Flow Rate

If a single-stage size separation sampler is to be used, the sample flow rate must be that which provides a 10-μm size cut. This flow rate will be determined by the gas composition and temperature of the process gas. The relationship between flow rate and gas parameters specific to the sampling device must be determined by calibration measurements (described in Section 2) prior to field use. For SRI/EPA Cyclone I, this relationship takes the form

$$Q_s = 0.002837 \left(\frac{M_w P_s}{T_s}\right)^{-0.2949} \mu. \qquad (5\text{-}3)$$

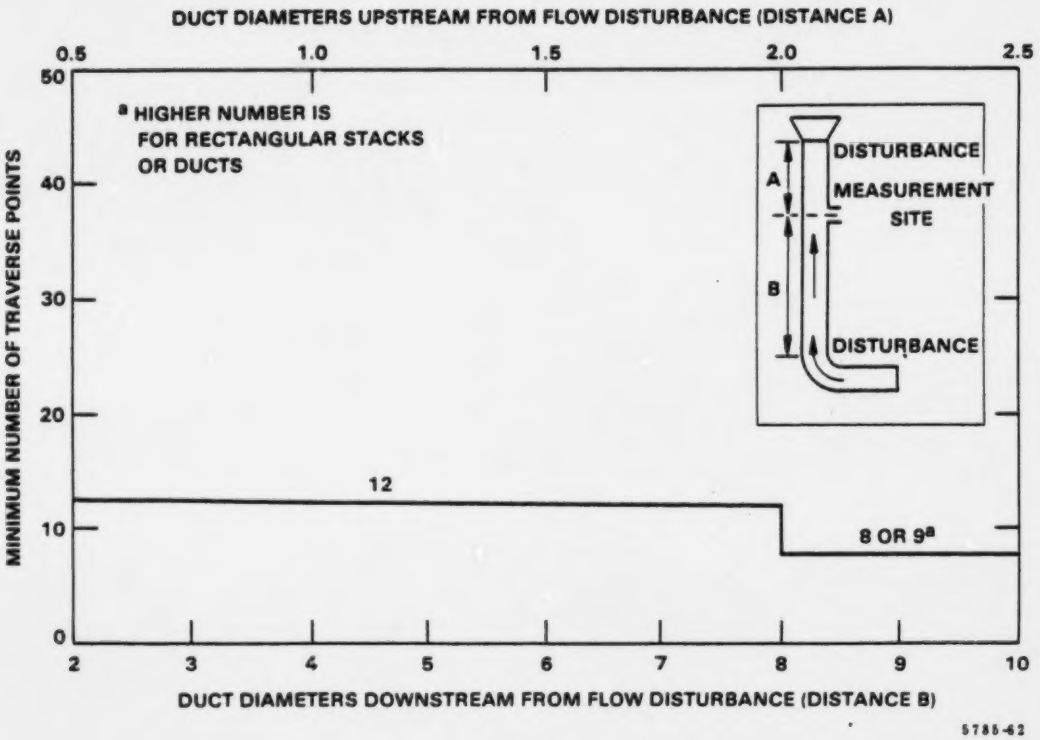


Figure 5-1. Minimum number of traverse points for CSR traverse.

The viscosity of the flue gas can be determined by the equation (Williamson et al., 1983)

$$\mu = C_1 + C_2 T_s + C_3 T_s^2 + C_4 B_{ws} + C_5 f_o \qquad (5\text{-}4)$$

where μ is in micropoise, T in °C, and

$C_1 = 160.62$
$C_2 = 0.42952$
$C_3 = 1.0483 \times 10^{-4}$
$C_4 = -74.143$
$C_5 = 53.147$

or for T in °R

$C_1 = 51.05$
$C_2 = 0.207$
$C_3 = 3.24 \times 10^{-5}$
$C_4 = -74.143$
$C_5 = 53.147$

This equation fits data (with a standard error of 0.98 micropoise) for combustion gas of arbitrary composition in the range 0-350 °C, 0-70% moisture. This equation was generated from large "data banks" of viscosities calculated by the more rigorous algorithm of Wilke (1950).

5.2.2 Nozzle Selection

After the sample flow rate has been determined, the corresponding nozzle velocity (u) for any given nozzle may be determined from the following equation:

$$u = \frac{4}{\pi d_n^2} Q_s \qquad (5\text{-}5)$$

For each nozzle velocity, a range of stack velocities, v_{min} to v_{max}, for which the anisokinetic sampling errors are within acceptable limits must then be determined. As discussed in Section 2, this range of stream velocities is governed by the semi-empirical relationship developed by Belyaev and Levin (1974)

$$A = 1 + (R - 1) \frac{B}{B + 1} \qquad (2\text{-}1)$$

where A = measured concentration/actual concentration
R = isokinetic ratio, v/u
B = $(2 + 0.617/R)K$
K = particle Stokes number with respect to the nozzle, $\tau v/d_n$
τ = particle relaxation time $CD^2/18\mu$, seconds
C = Cunningham slip factor
D = particle aerodynamic diameter
μ = gas viscosity, poise
d_n = nozzle diameter

Defining v_{min} as the stack velocity at which A equals 0.8 and v_{max} the stack velocity at which A equals 1.2, we obtain equations for v_{min} and v_{max} such that

$$v_{min} = u\left[0.2457 + \sqrt{0.3072 - \frac{0.2603\ Q_s^{1/2}\mu}{u^{3/2}}}\right] \quad (5\text{-}6)$$

$$v_{max} = u\left[0.4457 + \sqrt{0.5690 + \frac{0.2603\ Q_s^{1/2}\mu}{u^{3/2}}}\right] \quad (5\text{-}7)$$

where the terms in brackets are equivalent to the velocity ratios, R_{min} and R_{max}, respectively, and have additional limits of 1.0 ± 0.5 if more restrictive.

Although the v_{min} and v_{max} for a given nozzle are useful, the local stack velocity is actually measured as velocity pressure differentials during both Method 2 and CSR traverses. Therefore, it is more practical to convert v_{min} and v_{max} to the corresponding pressure differentials by using the following equations:

$$\Delta P_{min} = 1.3686 \times 10^{-4} \frac{P_s M_w}{T_s} \left(\frac{v_{min}}{C_p}\right)^2 \quad (5\text{-}8)$$

$$\Delta P_{max} = 1.3686 \times 10^{-4} \frac{P_s M_w}{T_s} \left(\frac{v_{max}}{C_p}\right)^2 \quad (5\text{-}9)$$

where C_p is the pitot coefficient of the CSR sampling probe, and all other variables are as defined previously.

Finally, given the most recent Method 2 data for the sampling plane and the ΔP limits for a given set of nozzles, the nozzle or nozzles required to perform the sample traverse may be determined. In instances where the pitot coefficients of the Method 2 probe and the CSR probe are different, the Method 2 data should be converted to equivalent values for the CSR pitot. This is accomplished by using the following equation:

$$\Delta P(\text{CSR}) = \Delta P(\text{Method 2})\left(\frac{C_p}{C_{p'}}\right)^2 \quad (5\text{-}10)$$

The ΔP limits for the chosen nozzle should bracket the measured stream values. If more than one nozzle is acceptable, the one giving the greatest symmetry should be selected. If the expected pitot ΔP for one or more points is near a limit for the chosen nozzle, it may be outside the limits at the time of the run due to temporal variations of the process.

5.3 SAMPLE FLOW RATE AND NOZZLE SELECTION FOR CASCADE IMPACTOR SAMPLERS

Several cascade impactors are available which can be used for PM_{10} measurement. The relationships between particle size cut, sample flow rate, gas composition, temperature, and nozzle diameter (for the first PM_{10} stage) must have been determined by calibration measurements (described in Section 2) before field sampling. Procedures for operating these devices, calculating particle size cut for each stage, and analysis of the results to obtain cumulative mass concentration as a function of particle size are described by McCain et al. (1986).

5.3.1 Sample Flow Rate

The multiple stages of a cascade impactor provide the ability to interpolate, thus permitting determination of PM_{10} without the requirement that a stage have a 10-μm size cut. This flexibility in flow rate permits minimization of error due to anisokinetic sampling by selection of a nozzle and flow rate corresponding to the average stream velocity, v, of the process stream. The sample flow rate is selected from the set, Q_n, determined by

$$Q_n = v \pi d_n^2/4 \qquad (5\text{-}11)$$

where Q_n = flow rate for nozzle n at the average stream velocity
d_n = diameter of nozzle n.

One of this set of flow rates is selected subject to the additional criteria below:

- The impactor must include one stage cut at or greater than 10 μm and two succeeding size cuts less than 10 μm.
- The separation between these successive size cuts must be no more than a factor of 2 and no less than a factor of 1.5.
- The product of jet velocity and size cut for each impactor stage with cut above 2 μm should satisfy the criteria given by McCain et al. (1986) for the particulate collection substrates utilized to limit particle bounce.

5.3.2 Nozzle Selection

Calculation of minimum and maximum stream velocities, v_{min} and v_{max}, for a given nozzle depends upon the desired accuracy for particles greater than 10 μm. If the >10-μm particulate fraction is of little concern, the calculation of v_{min} and v_{max} given for single-stage cyclones (equations 5-6 and 5-7) and similarly for ΔP_{min} and ΔP_{max} (equations 5-8 and 5-9) can be used. The errors in cumulative concentration versus particle size, due to anisokinetic sampling, will be limited to no more than ±20% at 10 μm, decreasing sharply

with particle size. The corresponding error for PM_{10} will be much less, depending upon the size distribution of the <10-μm particles.

If accurate measurement of particle sizes greater than 10 μm is sought, then the more restrictive limits of McCain et al. (1986), which require nozzle velocity to be within ±20% of the stream velocity at each traverse point, are recommended. In this case, the error limit of cumulative percent data for arbitrary size distribution is given by the percent deviation of nozzle velocity from stream velocity.

5.4 SAMPLE ORIFICE ΔH

After the sample flow rate and nozzle size have been determined, the orifice pressure drop, ΔH, corresponding to this sample flow rate may then be calculated from the following equation:

$$\Delta H = \left(\frac{Q_s(1 - B_{ws})P_s}{T_s}\right)^2 \; T_M M_d \left(\frac{1.083\ \Delta H_@}{P_a}\right) \qquad (5\text{-}12)$$

5.5 DWELL TIME

When EPA Method 5 or 17 is used for sampling, the dwell time at each traverse point is the same. The measured concentration is a velocity-weighted average for all points, as it should be for determination of emission rate, because the sampling rate is varied at each point proportionally to point velocity. Because flow rate cannot be adjusted from point to point with CSR, the dwell time at each point must be proportional to the point velocity to obtain a velocity-weighted sample.

The dwell time for the first sample point is calculated before the run is started in the following manner:

$$t_1 = \frac{\sqrt{\Delta P_1}}{(\sqrt{\Delta P})_{avg}} \; \frac{\text{(Total Run Time)}}{\text{(No. Points)}} \qquad (5\text{-}13)$$

where t_1 = dwell time at the first traverse point, min

ΔP_1 = the expected ΔP at the first traverse point (from a previous velocity traverse), in. H_2O

$(\sqrt{\Delta P})_{avg}$ = the average square root of ΔP from a previous velocity traverse

At subsequent traverse points, the velocity ΔP is measured and the dwell time calculated using the actual ΔP recorded at the first point such that

$$t_n = \frac{t_1}{\sqrt{\Delta P_1}} \sqrt{\Delta P_n} \qquad (5\text{-}14)$$

The number of minutes sampled at each point should be rounded to the nearest 1/4 min.

For sampling situations in which the stack temperature varies by more than ±50 °F, the temperature must be factored into the dwell time calculation to obtain a velocity-weighted sample. The dwell time equations become

$$t_1 = \frac{\sqrt{\Delta P_1 \; T_1}}{(\sqrt{\Delta P})_{avg} \sqrt{T_{avg}}} \; \frac{\text{(Total Run Time)}}{\text{(No. Points)}} \qquad (5\text{-}15)$$

$$t_n = \frac{t_1 \; \sqrt{\Delta P_n \; T_n}}{\sqrt{\Delta P_1 \; T_1}} \qquad (5\text{-}16)$$

where T_1 = stack temperature at the first traverse point, °R
T_{avg} = the average stack temperature (from a previous velocity traverse), °R
T_n = stack temperature at traverse point n, °R

The total sampling time given in equation 5-13 and 5-15 should be greater than or equal to the minimum total sampling time specified in the test procedures for the specific industry. Further, it is required that (1) the sampling time per point is not less than 2 min (or some greater time interval if specified by the Administrator) and (2) the sample volume taken (corrected to standard conditions) will exceed the required minimum total gas sample volume. The expected total volume of gas to be sampled during a single run may be approximated by using the sample flow rate and average run time.

In some circumstances (e.g., batch cycles) it may be necessary to sample for shorter times at the traverse points and to obtain smaller gas sample volumes. In these cases, the approval of the Administrator should be obtained.

5.6 PERFORMING THE CALCULATIONS

Calculation with the equations presented in the previous subsections may be performed in a number of ways. A set of worksheets to be used for hand calculation of the setup equations has been prepared. These worksheets are shown in Figures 5-2, 5-3, and 5-4.

If the stack gas temperature changes such that it is outside ±50 °F of the average used for the setup calculations, the setup parameters (sample orifice ΔH and nozzle ΔP limits) should be recalculated. To save time during the run, it is recommended that the setup calculations be performed prior to sampling for a range of average stack temperatures. These temperatures should be in increments of 50 degrees and span the range of expected stack temperatures. This limits errors in the sample flow rate and nozzle ΔP limits to approximately ±10%. A table is included in Figure 5-4 to facilitate this approach.

CSR WORKSHEET I

SAMPLE FLOW RATE AND ORIFICE ΔH

Barometric Pressure, P_a, in. Hg = _____

Stack Differential Pressure, $D_{P\ stack}$, in. H_2O = _____

Average Stack Temperature, T_s, °R = _____

Meter Temperature, T_M, °R = _____

Orifice $\Delta H_@$, in. H_2O = _____

Gas Analysis:

CO_2 fraction, f_c = _____

O_2 fraction, f_o = _____

Water fraction, B_{ws} = _____

$$M_d = 44(f_c) + 32(f_o) + 28(1 - f_c - f_o) = _____$$

$$M_w = M_d(1 - B_{ws}) + 18(B_{ws}) = _____$$

$$P_s = P_a + \frac{D_{P\ stack}}{13.6} = _____$$

$$\mu = 51.05 + 0.207\ T_s + 3.2355 \times 10^{-5}\ T_s^2 + 53.147(f_o) - 74.143(B_{ws}) = _____$$

$$Q_s = 0.002837 \left[\frac{M_w\ P_s}{T_s}\right]^{-0.2949} \mu = _____$$

$$\Delta H = \frac{[Q_s\ (1 - B_{ws})\ P_s]^2}{[T_s]^2}\ T_M\ M_d \left[\frac{1.083\ \Delta H_@}{P_a}\right] = _____$$

Figure 5-2. CSR worksheet I - sample flow rate and orifice ΔH calculations.

CSR WORKSHEET II

NOZZLE SELECTION

Barometric Pressure P_a, in. Hg = _____

Stack Differential Pressure, $D_{p\ stack}$, in H_2O = _____

Average Stack Temperature, T_s, °R = _____

Meter Temperature, T_M, °R = _____

Sample Flowrate, Q_s, acfm = _____

Gas Analysis:

CO_2 fraction, f_c = _____

O_2 fraction, f_o = _____

Water fraction, B_{ws} = _____

CSR Pitot Coefficient, C_p = _____

Method 2 Pitot Coefficient, C_p' = _____

$M_d = 44(f_c) + 32(f_o) + 28(1 - f_c - f_o)$ = _____

$M_w = M_d(1 - B_{ws}) + 18(B_{ws})$ = _____

$$P_s = P_a + \frac{D_{p\ stack}}{13.6} = \text{_____}$$

$$\mu = 51.05 + 0.207\ T_s + 3.2355 \times 10^{-5}\ T_s^2 + 53.147(f_o) - 74.143\ B_{ws} = \text{_____}$$

$$u = \frac{3.056\ Q_s}{d_n^2} = \text{_____}$$

Figure 5-3. CSR worksheet II - nozzle selection.

$$v_{min} = u \left[0.2457 + \sqrt{0.3072 - \frac{0.2603\ Q_s^{1/2}\ \mu}{u^{3/2}}} \right]$$

$$v_{max} = u \left[0.4457 + \sqrt{0.5690 + \frac{0.2603\ Q_s^{1/2}\ \mu}{u^{3/2}}} \right]$$

$$\Delta P_{min} = 1.3686 \times 10^{-4} \frac{P_s\ M_w}{T_s} \left(\frac{v_{min}}{C_p} \right)^2$$

$$\Delta P_{max} = 1.3686 \times 10^{-4} \frac{P_s\ M_w}{T_s} \left(\frac{v_{max}}{C_p} \right)^2$$

Nozzle ID				
d_n, in.				
u, fps				
v_{min}, fps				
v_{max}, fps				
ΔP_{min}, in. H_2O				
ΔP_{max}, in. H_2O				

Velocity Traverse Data:

$$\Delta P(CSR) = \Delta P(\text{Method 2}) \left(\frac{C_p}{C_p'} \right)^2 = _____$$

	Port_____		Port_____		Port_____		Port_____	
Point #	ΔP	Noz ID	ΔP	Noz ID	ΔP	Noz ID	ΔP	Noz ID
1	____	_____	____	_____	____	_____	____	_____
2	____	_____	____	_____	____	_____	____	_____
3	____	_____	____	_____	____	_____	____	_____
4	____	_____	____	_____	____	_____	____	_____

Figure 5-3. (Continued).

CSR WORKSHEET III

DWELL TIME

Previous Method 2 data: Total Run time, min. = _____

No. Traverse points = _____

$(\sqrt{\Delta P})_{avg}$ = _____ Average T_s °R = _____ $\sqrt{\Delta P_1}$ = _____

$$t_1 = \frac{\sqrt{\Delta P_1}}{(\sqrt{\Delta P})_{avg}} \frac{\text{Total run time}}{\text{No. points}} \quad t_n = \frac{t_1}{\sqrt{\Delta P_1}} \sqrt{\Delta P_n}$$

Note: If T_s varies by more than ±50°F from the average, T_s must be included in the dwell time calculations as shown in Equations 5-15 and 5-16, which include the factors $\sqrt{T_1/T_{avg}}$ and $\sqrt{T_n/t_1}$ in the equations for t_1 and t_n, respectively.

T_s, °F								
ΔH, in. H_2O								
d_n, in.	ΔP_{min}	ΔP_{max}	ΔP_{min}	ΔP_{max}	ΔP_{min}	ΔP_{max}	ΔP_{min}	ΔP_{max}

	Port _____		Port _____		Port _____		Port _____	
Point #	Δp	t	Δp	t	Δp	t	Δp	t
1								
2								
3								
4								

Figure 5-4. CSR worksheet III - dwell time calculations.

SECTION 6

TAKING THE SAMPLE

6.1 FIELD ASSEMBLY

After the sampling system has arrived at the test site, it should be visually inspected to determine if any damage was incurred during transport. To check for internal probe damage, a positive-pressure leak check on each of the lines running through the probe is recommended. To do this, one end of each line should be blocked and positive pressure applied at the other. The pressure on the line should be monitored with a manometer connected in parallel. Failure to hold pressure indicates an internal probe leak, which should be found and repaired before proceeding.

When it has been determined the system is in proper operating condition, the operator should begin assembling the system. The particle-sizing device should be assembled as the operating manual dictates. The sampling nozzle should then be attached to the sampler and the complete device mounted on the probe. With the proper length of extension tubes, the pitot head should then be mounted on the probe. The sampling nozzle and one leg of the pitot must face the same direction while all the tubing unions are fully tightened. A combined umbilical or individual tubing can then be used to connect the probe to the control console. The sample line should be attached to the inlet of the water dropout system (condenser and silica gel column), which is, in turn, attached to the sample inlet of the control console. If available, an umbilical which encloses the sample line and thermocouple extensions in a single sheath is preferred.

Because the amount of water collected in the condensing system must be known, all components of this system should be clean and free of any foreign material. If silica gel columns are used, a preweight of the column and silica gel should be obtained before any testing. Then the column must be sealed until testing commences to avoid any accidental uptake of moisture. After sampling, the column should be weighed again to determine the amount of water uptake. If a condenser is used, it should be placed in an ice chest and ice added to the chest until the condenser is sufficiently covered.

6.2 LEAK TEST

When the system has been completely assembled, the control console pump may be used to leak-check the vacuum system as in Method 5:

- Plug the sampling nozzle and turn on the pump to produce a vacuum across the desired test section.
- Use the fine-adjust valve to set the system vacuum to 15 in. Hg.

If the required vacuum reading on the console-mounted vacuum gauge cannot be achieved or if the gas meter indicates a leak rate greater than 0.02 cfm, the system is not sealed, and the leak(s) must be located and fixed.

The positive pressure portion of the control console can be tested for leaks by using the procedure described in Method 5.

6.3 PRETEST EQUIPMENT WARM-UP

Because most flue streams to be tested are not at ambient temperatures, the CSR sampling device must be heated to stack conditions. This helps ensure isokinetic sampling and significantly reduces the chance of acid deposition within the sample line. The sampler should be heated in the gas stream long enough to equilibrate with the temperature of the surrounding stack gases. Typically, the PM_{10} sampler should remain in the flue at least 15-20 min to ensure thermal equilibrium. The nozzle, if uncapped, should not point into the flow field during preheating. If possible, the nozzle should be capped or plugged during preheating, and the cap or plug should be removed immediately before sampling.

If the absolute pressure of the gas stream to be sampled is significantly lower than ambient pressure, care must be taken to prevent rupturing the filter when the sampler is inserted into the duct. In Method 5, this problem may be avoided by starting the pump as the probe is inserted through the port. Because of the preheat required with CSR, this method cannot be used.

If an in-stack filter configuration is used, the sample line should be closed at the back end of the probe. However, because enough gas volume remains in the probe to rupture the filter, steps must be taken to slowly insert the probe into the stack. This allows the probe to gradually adjust to the duct vacuum without rupturing the filter.

If the system is operated in a Method 5 configuration, a heated probe should be used. The heating system should be adjusted to maintain a probe temperature slightly greater than the gas dew point. If an in-stack filter is used, a heated probe is not necessary. However, care should be used to prevent condensed vapors from running back into the sampler. One solution is to keep the probe inclined during operation.

6.4 SYSTEM START-UP

After the sampling device has preheated a sufficient length of time, the nozzle cap (if one is used) should be removed and the nozzle turned into the flow. The vacuum pump should be started and the sample line opened simultaneously. The sample orifice ΔH should then be adjusted to the appropriate setting. The dwell time at the first traverse point should be that calculated from equation 5-13. The dwell time at each subsequent point should be calculated during the run from equation 5-14.

If the stack temperature at any point in the traverse falls outside ± 50 °F of the average used to calculate the operating parameters, a new temperature range should be chosen and the operating parameters (ΔH and

nozzle ΔP limits) corresponding to this new temperature range should be used. Dwell times should be calculated using equations 5-15 and 5-16.

6.5 TRAVERSING

During traversing (moving to a new point or new port), all motion should be smooth and brief to avoid bumping or vibrating the sampler. When removing or inserting the sampler, care must be taken not to scrape the nozzle on the port wall. Also, the sampler should not be allowed to bump against the far inside wall of the duct.

6.6 SHUTDOWN ORIENTATION

The orientation of the sampler may require the operator to maintain an appreciable flow rate while removing the sampler from the flue. The flow rate should be maintained until the sampler can be placed in a favorable orientation (usually horizontal). This is particularly true when operating a cyclone in a vertical orientation. Otherwise, some dust might fall from one stage of the sampler to another and thus be measured where it was not collected. Special care must be exercised to prevent contamination of the sample by dust from the walls of the port. After the flow has been terminated, the sampler can be transported to the laboratory. The sampler should be kept in a horizontal position with the nozzle plugged or covered to avoid contamination or loss of sample.

6.7 DATA LOGGING

The parameters of the test should be recorded in a clear, concise format like that shown in Figure 6-1. Parameters that are likely to change, such as stack temperature and velocity ΔP, should be recorded periodically. After sampling at the first point, move to the next and immediately compare the pitot Δ.

Run Code	Date	Stack Temperature (°F)
Sampler ID	Start Time	Differential Stack Pressure (in. H_2O)
Filter ID	End Time	Ambient Temperature (°F)
Sampler Orientation	Sampling Duration (min)	Ambient Pressure (in. Hg)
Sampling Location	DGM (initial)	Gas Velocity
Nozzle Diameter-ID (in)	DGM (final)	System Leak Check
Operator(s)	Sample Volume (ft^3)	
Dual Manometer Leveled and Zeroed?		
Magnehelics Zeroed?		
Gas Composition %CO_2 %O_2 %CO	Pitot Leak Check (Pos) (Neg)	Notes
Moisture Content		

Run Time	Port No / Trav.Pt.	ΔP Pitot	ΔH Sample	DGM Volume	T Stack	T Probe	T DGM	Dwell Time[a]

[a]Dwell Time, $t_n = \frac{t_1}{\sqrt{\Delta P_1}} \sqrt{\Delta P_n}$

Figure 6-1. CSR field data sheet.

SECTION 7

SAMPLE RETRIEVAL

After the sampling system has been allowed to cool to a point where it can be safely handled, the collected sample may be carefully recovered. The recovery procedures described below are specifically for the configuration of SRI/EPA Cyclone I. Different sampling devices may have different sample recovery procedures, as described in the manufacturer's operating manuals and in the literature.

7.1 RECOVERY OF THE PARTICULATE MASS

Great care is needed during recovery of the collected particles from the PM_{10} sampler to ensure that all of the particulate matter is recovered and placed in the proper sample containers. The sample can be effectively recovered from both stages of the PM_{10} sampler (cyclone and filter) by using a combination of brushing and washing.

The first step in recovery of the particulate matter from the nozzle and cyclone is brushing the collected mass into the appropriate foil envelope. A clean no. 7 camel's hair brush or small nylon bristle brush is suggested for this operation. The brushed surfaces should then be rinsed thoroughly with acetone, or similar solvent, to recover any particles that continue to adhere to the sampler. These rinses should be collected in a uniquely identified sample container. The brush used for recovery should also be rinsed into this container.

The filter should be recovered from the filter holder and returned to the appropriate container. Any particulate matter or filter fibers adhering to the filter holder surfaces or rubber O-ring should be brushed onto the surface of the filter. The interior surfaces of the filter holder should then be rinsed with the solvent as described above.

As stated previously, assignment of the collected particulate matter to the appropriate sample container is very important. Particulate matter collected on the inner surfaces of the nozzle, the cyclone body, collection cup and cap are to be considered as collected by the cyclone. Furthermore, any matter brushed or rinsed from the <u>outside</u> of the cyclone exit tube is also to be considered part of the cyclone catch. The PM_{10} fraction consists of particulate matter collected from the inner surface of the "turn-around" on the cyclone cap, the <u>inside</u> wall of the exit tube, the inner walls of the filter holder (upstream of the filter), and the surface of the filter.

Final weights for all particulate samples should be determined on site, prior to shipment. Recommended procedures are outlined in Section 8.

7.2 MOISTURE DETERMINATION

The condenser should be drained of any collected moisture and the amount of liquid determined either volumetrically (to ± 1 mL) or gravimetrically (to ± 0.5 g). The liquid may be discarded after the weight or volume is recorded. The spent silica gel should be weighed in the appropriate container (such as the drying column or shipment container) to determine the moisture uptake.

SECTION 8

POSTSAMPLING CHECKS

Posttest activities for a CSR system involve equipment calibration checks, field sample analysis, and equipment maintenance. The first two items are discussed in this section. The third item is discussed in Section 10 of this manual.

8.1 EQUIPMENT CALIBRATION CHECKS

A posttest calibration check of the flow metering devices is required. The posttest calibration check should be performed as described in Section 3 of this manual. If the gas meter correction factor obtained from the calibration check deviates from the initial calibration factor by more than 5%, the meter should be recalibrated. The posttest data reduction should then be performed with whichever calibration factor yields the lower gas meter volumes.

Calibration checks should also be performed on the stack and dry gas meter thermocouples. Each of the above temperature sensors should be compared with a mercury-in-glass thermometer at ambient temperature. If the stack temperature thermocouple reading differs from the reference by more than 1.5% of the absolute temperature, the thermocouple should be recalibrated as described in Section 3. The old and new calibrations should be compared to determine the sign and magnitude of the correction to be applied to the average stack temperature. If the dry gas meter thermocouple reading varies from the reference by more than 6 °C (10.8 °F), the thermocouple should be recalibrated. For data reduction calculations, the calibrations which give the higher gas meter temperature should be used.

A posttest calibration check is also required for the system Magnehelic® gauges. This calibration check should be performed as described in Section 3.

8.2 SAMPLE ANALYSIS

Analysis of the field samples is essentially the same as for Method 5. Filter and cyclone catches should desiccate for a minimum of 24 h before the initial weighing. Each sample should be weighed to a constant weight, which is achieved when the difference between consecutive weighings is no more than 0.5 mg or 1% of the total weight less tare weight, whichever is greater; at least 6 h of desiccation time should be allowed between weighings.

As an alternative, the samples may be oven dried at the average stack temperature or 220 °F, whichever is less, for 2 to 3 h, cooled in a desiccator, and weighed to a constant weight. The tester may also opt to oven dry the samples as described above, weigh the samples and use this as the final weight. Whichever option is chosen, final weights of all cyclone and filter samples should be determined to the nearest 0.1 mg on site, before shipping.

Acetone rinse and blank samples should be inspected to confirm that no leakage has occurred. If a noticeable amount of sample has been lost through leakage, the sample must be either declared void or corrected in the final results with methods approved by the sponsoring agency. The liquid should be measured either volumetrically to ±1 mL or gravimetrically to ±0.5 g. Each sample should be evaporated to dryness at ambient temperature and pressure in a tared 250-mL beaker or similar container. The evaporated samples should be desiccated for 24 h and weighed to a constant weight. Results should be recorded to the nearest 0.1 mg.

If the silica gel is not analyzed in the field, the spent silica gel samples should be weighed in the appropriate container to the nearest 0.5 g.

SECTION 9

DATA ANALYSIS

9.1 VELOCITY-WEIGHTED AVERAGES

If the velocity distribution at the sampling plane is such that two or more nozzle sizes are required to complete a traverse or if the stack temperature variation exceeds ±50 °F so that new setup parameters are required during the run, a velocity-weighted average of the stack temperature and particulate concentration must be calculated. For a generic data term, D, this equation takes the form

$$\overline{D} = \frac{1}{\theta} \sum_{j=1}^{n} D_j \, t_j \qquad (9\text{-}1)$$

where $\overline{D}$ = the velocity-weighted average of D
D_j = average value of D for each nozzle size
θ = total run time
t_j = run time for each nozzle size
n = number of component changes

For the remainder of this section, the term "run" will refer to that portion of a traverse performed without any component changes.

9.2 DRY GAS METER VOLUME

The sample volume measured by the dry gas meter can be corrected to standard conditions (68 °F, 29.92 in. Hg) by using the following equation:

$$V_{MS} = (V_M \, Y) \left(\frac{T_{ST}}{T_M}\right) \left(\frac{P_a + \frac{\Delta H}{13.6}}{P_{ST}}\right)$$

$$= 17.65 \left(V_M \, Y\right) \left(\frac{P_a + \frac{\Delta H}{13.6}}{T_M}\right) \qquad (9\text{-}2)$$

9.3 VOLUME OF WATER VAPOR

The volume of the water vapor collected from flue gas is calculated as follows:

$$V_{WS} = V_{lc} \frac{\rho_{H_2O}}{M_{H_2O}} \frac{R_u T_{ST}}{P_{ST}}$$

$$= 0.04707 \, V_{lc} \qquad (9\text{-}3)$$

9.4 PERCENT MOISTURE CONTENT

The moisture content of the stack (or sample) gas is calculated by the equation

$$B_{ws} = \frac{V_{WS}}{V_{MS} + V_{WS}} \tag{9-4}$$

9.5 STACK GAS MOLECULAR WEIGHT

$$M_d = 32(f_o) + 44\ (f_c) + 28\ (1 - f_o - f_c) \tag{5-1}$$

$$M_w = M_d\ (1 - B_{ws}) + 18\ (B_{ws}) \tag{5-2}$$

9.6 STACK GAS VISCOSITY

The viscosity of the stack gas may be calculated from the following equation (Williamson et al., 1983):

$$\mu = C_1 + C_2 T_s + C_3 T_s^2 + C_4 B_{ws} + C_5 f_o \tag{5-4}$$

where μ is in micropoise, T in °C, and

$C_1 = 160.62$
$C_2 = 0.42952$
$C_3 = 1.0483 \times 10^{-4}$
$C_4 = -74.143$
$C_5 = 53.147$

or for T in °R

$C_1 = 51.05$
$C_2 = 0.207$
$C_3 = 3.24 \times 10^{-5}$
$C_4 = -74.143$
$C_5 = 53.147$

9.7 SAMPLE FLOW RATE

The sample flow rate, at standard conditions, can be found by using the following equation:

$$Q_{S_{ST}} = \frac{V_{MS}}{\theta} \tag{9-5}$$

However, to calculate the particle cut diameter of the inertial classifier, it is necessary to know the flow rate through the sampler at the actual sampler conditions. This can be accomplished by using the following equation:

$$Q_s = Q_{s_{ST}} \left(\frac{1}{1 - B_{ws}}\right) \left(\frac{T_s}{T_{ST}}\right) \left(\frac{P_{ST}}{P_s}\right)$$

$$= 0.056 \; Q_{s_{ST}} \left(\frac{1}{1 - B_{ws}}\right) \left(\frac{T_s}{P_s}\right) \qquad (9\text{-}6)$$

9.8 SAMPLER D_{50}

The D_{50} or cut-point of each stage of the chosen particle-sizing device should be calculated for accurate determination of the particle size distribution. The cut-point is primarily a function of the actual flow rate through the sampler and the viscosity and density of the stack gas.

The currently available data concerning calibration of the SRI/EPA Cyclone I show the behavior to be described by the equation

$$D_{50} = 0.15625 \left(\frac{M_w P_s}{T_s}\right)^{-0.2091} Q_s^{-0.7091} \mu^{0.7091} \qquad (9\text{-}7)$$

If another inertial sizing device is used in conjunction with CSR, the D_{50}'s for each of the stages should be calculated as described in the vendor-supplied operator's manual.

9.9 STACK GAS VELOCITY

The stack gas velocity can be found by using the following equation:

$$v_s = K_p C_p \left(\sqrt{\Delta P}\right)_{avg} \left(\frac{T_s}{P_s M_w}\right)^{1/2} \qquad (9\text{-}8)$$

9.10 NOZZLE VELOCITY

The nozzle velocity (u), constant for a specific nozzle diameter (d), may be calculated from the following equation:

$$u = \frac{3.056 \; Q_s}{d^2} \qquad (9\text{-}9)$$

9.11 NOZZLE ΔP LIMITS

For each nozzle and stack gas temperature range, limits on acceptable velocity pressure differentials, ΔP_{min} and ΔP_{max}, were calculated from equations 5-8 and 5-9 of the setup calculations. To determine if the run was performed within these limits, the actual stack temperature and velocity ΔP at each traverse point should be tabulated and compared with the limits, ΔP_{min} and ΔP_{max}, for the appropriate temperature range. If the stack temperature varies by more than ±50 °F from the average, the run will have more than one set of Δp limits.

9.12 PERCENT ISOKINETIC SAMPLING

The following equation should be used to determine the percentage of isokinetic sampling:

$$I\% = \frac{1.677\ T_s \left[0.00267\ V_{lc} + \frac{V_M Y}{T_m}\left(P_a + \frac{\Delta H}{13.6}\right)\right]}{\theta\ v_s\ P_s\ A_n} \qquad (9\text{-}10)$$

9.13 CONCENTRATION

The concentration of the particulate matter caught by each stage in grains per standard cubic foot can be calculated by the equation below

$$C'_m = 0.0154\ \left(\frac{M_p}{V_{MS}}\right) \qquad (9\text{-}11)$$

The units can be converted to milligrams per dry normal cubic meter by using the following:

$$C_m = 2293.2\ C'_m \qquad (9\text{-}12)$$

9.14 ACCEPTANCE CRITERIA

To be acceptable, each run must meet the following criteria:

1) The velocity at each traverse point must be within the velocity limits for the nozzle used, or the velocity at one point may be below the minimum for the nozzle if the percent isokinetic falls within 100 ± 20%. This second specification allows for the acceptance of data with a positive bias but which are still within allowable error limits.
2) For single stage PM_{10} samplers

   - D_{50} must be 10 ± 1 µm.

   For multiple stage PM_{10} samplers

   - one stage cut must be at or greater than 10 µm and two succeeding size cuts must be less than 10 µm
   - separation between successive size cuts must be no more than a factor of 2 and no less than a factor of 1.5
   - the product of jet velocity and size cut for each stage with cut above 2 µm should satisfy the criteria given by McCain et al. (1986).

SECTION 10

MAINTENANCE

A notebook or other record of all maintenance procedures should be kept. This will provide a definite and current record of all information pertinent to reliable operation of the CSR sampling system. Maintenance of the system should be performed as described previously (Rom, 1972), with the exceptions noted below.

10.1 VACUUM SYSTEM

The vacuum system may be checked as follows:

- Insert a plugged 0.5-in. male quick connect into the sample inlet of the control console.
- Turn the pump switch to ON.
- Turn the coarse-adjust valve to the ON position.
- Close fully the fine-adjust valve.

The vacuum gauge should read about 25 in. Hg when ambient barometric pressure is near 30 in. Hg. If this pressure cannot be achieved, a leak or sticking pump vane should be suspected. If the leakage rate measured by the dry gas meter exceeds 0.02 cfm, the leak or leaks must be found and corrected. Parts to check are the pump, vacuum gauge, metering valves, and tubing.

10.2 VACUUM PUMP

Most pump trouble can be corrected by flushing the unit according to the manufacturer's instructions rather than disassembly. A noisy or inefficient pump is frequently caused by nothing more serious than a vane stuck in a rotor slot because of foreign material in the unit. To flush the unit, follow the procedure given below:

- Separate the pump from the system.
- Slowly add several teaspoons of solvent at the intake while the unit is running (recommended commercial solvents include Loctite Safety Solvent, Inhibisol Safety Solvent, or Dow Chemical Chlorothane).
- Lay the unit on its side with the outlet downward so the solvent will work out again.

10.3 MAGNEHELIC® DIFFERENTIAL PRESSURE GAUGES

Magnehelic® differential pressure gauges are precision instruments assembled and precalibrated by the manufacturer. If trained instrument mechanics are not available, it is recommended that any instruments requiring repair be returned to the factory.

No lubrication or periodic servicing is required. If the interior is protected from dust, dirt, and corrosive gases and fluids, years of trouble-free service may be expected.

10.3.1 Zero Adjustment

The indicating pointer should be set exactly on the zero mark by using the external zero-adjust screw on the cover at the bottom. The zero check or adjustment can be made only if the high-pressure and low-pressure taps are both open to atmosphere.

10.3.2 Calibration Check

For service requiring a high degree of continued accuracy, periodic calibration checks are recommended. In general, the Magnehelic® calibration should be checked by following the procedure below.

1. As a comparison gauge, use a hook gauge, micromanometer, or inclined gauge of known accuracy.

2. Connect the Magnehelic® gauge and reference gauge with two leads from a "T." Connect rubber tubing to the third leg of the "T," and impose the pressure, slowly.

3. Be certain no leaks exist in the system, and provide adequate time for comparison gauges to reach equilibrium, because fluid drainage and different dynamic characteristics can affect the reading.

10.3.3 Recalibration

1. Remove the plastic cover.

2. Remove the two screws holding the scale, and slide the scale out, using care not to damage the pointer.

3. Loosen the two set screws in the range spring clamp (Dwyer part no. NUA-70B); move toward the helix to increase the range and back to decrease. Secure the clamp with the set screws, replace the scale, check the gauge zero, and compare readings as in Section 10.3.2.

4. Replace the cover. The cover must be tight and leakproof for accurate readings on the high-pressure side. Observe the following procedure.

   a. Place the cover in position with the notch engaged and with the O-ring properly seated.

b. Jockey the zero-adjust screw into position so its hex end is inserted in the socket set screw, which actuates the zero-adjusting mechanism.

c. Hold the cover in position and screw the bezel down snuggly. The O-ring must take some squeeze to effect an airtight seal.
Caution: If the bezel binds because of galling action of aluminum surfaces, lubricate sparingly with light oil or molybdenum sulfate compound.

d. Troubleshooting.

1. Gauge sluggish.
   - Leads may be plugged or leaking.
   - Cover may be loose or leaking.
   - Pointer may be touching scale.
   - Jewels supporting helix may be overtightened.
2. Gauge fails to indicate zero properly.
   - See comments above regarding sluggish readings.
   - Iron particles may be in a strong magnetic field between helix and magnet. If found, they may be removed by touching each particle and withdrawing it with a small screw driver.
   - Magnet may be shifted and touching helix.
3. Apparent inaccuracy.
   - See preceding comments.
   - Improper connections to pick up desired differential.
4. Consult factory for unusual conditions of temperature, pressure, etc., and the effect on gauge operation and accuracy.

10.4 DUAL MANOMETER

The dual manometer may be checked as follows:

- Visually check the pitot and orifice manometer lines to ensure they are free of fluid.

- Check for leaks, especially around the fluid-level zeroing controls and drain screws.

- Wipe the dual manometer clean. The back can be cleaned with compressed air, or the device can be removed from the control panel and wiped clean.

- If the dual manometer is unusually dirty, clean as recommended on the instruction plate.

- Make sure that the manometer ports are open (1-1/2 turns counter-clockwise from the seat) and the manometer lines are connected.

- Level the manometer and check the fluid level.

- To fill the manometer with fluid, remove the screw on the left side. When the oil meniscus and the reflected image at zero are aligned, the fluid-level plunger (zeroing control) should have about 1/4 to 1/2 in. travel inward.

Note: During rough shipment, the manometer lines should be disconnected and the manometer ports closed by turning clockwise until sealed.

- If for any reason the manometer unit has been inverted, be sure the floating check valves of the manometer have returned to their normal position. These floating valves are located under the manometer ports and must be in the normal position when the manometer is used.

10.5 PITOT TUBE

The pitot tube should occasionally be inspected for any deformation of the pressure inlets, because this may change the pitot calibration coefficient. Any dents or nicks should be repaired or the pitot head should be replaced if the damage warrants it. Before each test run, the operator should blow gently into each pitot inlet to check for obstructions. If the pitot tube lines are clear, the pitot tube gauge will respond. If no response is noted, the operator should blow out the pitot lines with compressed air. The pitot tube can be checked for leaks by plugging one end of the tube and applying a positive pressure at the opposite end. If the tube will not maintain pressure, a soap solution can be used to identify the location of any leaks.

10.6 NOZZLES

The sample nozzle should be visually inspected before any testing. If repair is necessary, a plumb bob should be used for inside damage and emery paper for outside damage. After any nozzle repair, the nozzle diameter should be remeasured. The knife edge of the nozzle should be covered with serum caps or similar covers to avoid damage when the nozzle is not in use.

10.7 THERMOCOUPLES

The thermocouples throughout the system should occasionally be checked against room temperature by using a mercury-in-glass thermometer as the standard. If any thermocouples do not read within ±5 °C, the thermocouples or readout should be replaced or recalibrated.

10.8 SAMPLING PROBE

10.8.1 Probe Cleaning

Before each field test, all lines of the sampling probe, including the pitot tube lines, should be cleaned according to the procedure outlined below.

- Clean the probe internally by rinsing, first with tap water, then with distilled, deionized water, then with acetone or dichloromethane.

- Rinse the internal tubes with the chosen organic solvent and allow them to air dry.

- Visually inspect the probe for cleanliness, and repeat the procedure if necessary.

- Rinse the pitot lines with water and blow them out with compressed air.

10.8.2 Probe Heater Check

The procedure below may be used to check the probe heater.

- Plug the probe heater line and controlling thermocouple into the control case, and turn the heat controller on.
  The indicator light on the controller should come on, and the probe should become warm to the touch in a few minutes. After a few minutes, the indicator light should begin to cycle on and off.

- If the probe does not heat, check the probe for loose connections.

- If the probe still does not heat, remove the probe liner from the probe sheath for inspection of the heating element.

- After the probe lines have been removed, unwrap the insulation and visually inspect the probe heating element for shorts or burned spots. An ohmmeter can also be used to measure the resistance between leads (approximately 17 ohms) and also to ground (infinite). Deviations from these values indicate faulty wiring.

- After any electrical problem has been solved, rewrap the probe lines with insulating material, and reassemble the probe.

10.9 CONDENSING SYSTEM

If the CSR sampling train is operated in a Method 17 configuration, a condenser and silica gel column may replace the Method 5 impinger train assembly. An impinger system will be required if the "back-half" catch is to be measured. Whichever system is used for collection of water vapor from the sampled stack gas, it must be clean and free of leaks before being used. Glass impingers should be cleaned with distilled, deionized water and then acetone and should then be allowed to air dry. Stainless steel condensers should also be rinsed by the same procedure and allowed to air dry, inverted to ensure total drainage. The drying can be speeded by blowing out the condenser with compressed air. Silica gel columns (along with condensers) should be leak tested, along with the control box or separately, by applying positive pressure at the inlet and plugging the outlet. Ideally, these devices should maintain a pressure of at least 10 in. Hg above absolute.

SECTION 11

AUDITING PROCEDURES

Routine quality assurance activities, such as equipment calibrations, are essential to obtaining good data. An assessment of the quality of these data may be made through an audit. The audit must be performed with equipment or standards independent of those used for actual measurements to ensure that the tasks involved are being performed properly.

The audits recommended for use in a program using the CSR method are similar to those described for Method 5 (U.S. Environmental Protection Agency, 1977, Section 3.4.8). Two types of audits, performance and system, are commonly performed.

Performance audits provide a quantitative evaluation of the quality of data produced by a measurement system. One type of performance audit recommended for Method 5 assesses the accuracy of a system's flow metering devices with a critical flow orifice. This is also recommended for measurement programs using the CSR.

A performance audit of data processing is also recommended. As for Method 5, an audit of this type can uncover and eliminate errors in data transfer, calculations, etc. The flow of data from field data forms and weight sheets to data reduction programs or hand calculations should be traced for at least a portion of the data base. Calculation of results for a standard data set is another method by which data reduction procedures may be audited.

A system audit is a qualitative inspection and examination of the procedures and techniques used by the field team. This type of audit is strongly recommended if the team is not familiar with the CSR method.

SECTION 12

RECOMMENDED STANDARDS FOR ESTABLISHING TRACEABILITY

Although the use of quality control checks and independent audits is essential to obtaining data of the desired quality, another important consideration is the traceability of individual elements of the measurement process. All materials, equipment, and procedures used should be traceable to a standard of reference.

Working calibration standards should be traceable to primary or higher level standards. The system's flow metering devices should be calibrated against a wet test meter which has been verified as required for Method 5 (U.S. EPA, 1977). The performance of the analytical balance should be checked against class-S weights that are traceable to NBS standards.

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GLOSSARY

Aerodynamic diameter: The aerodynamic diameter of a particle is the diameter of a sphere of unit density whch has the same settling velocity in the gas as the particle of interest. For spherical particles with diameter Dp, larger than a few microns and gas conditions of interest for source PM_{10}, the aerodynamic diameter is essentially given by $\sqrt{\rho_p}\ D_p$ where ρ_p is the particle density.

Cut-point: The cut-point of a size classifier is the particle diameter for which all particles of equal or greater diameter are captured and all particles with smaller diameters are not captured. No real device actually has a sharp step function cut-point, but the theoretically defined D_{50} of a stage is often called its cut-point.

Geometric standard deviation, σ_g: A measure of dispersion in a lognormal distribution. It can be calculated as the ratio of particle diameter corresponding to a cumulative percent of 50 to the diameter corresponding to a cumulative percent of 15.86.